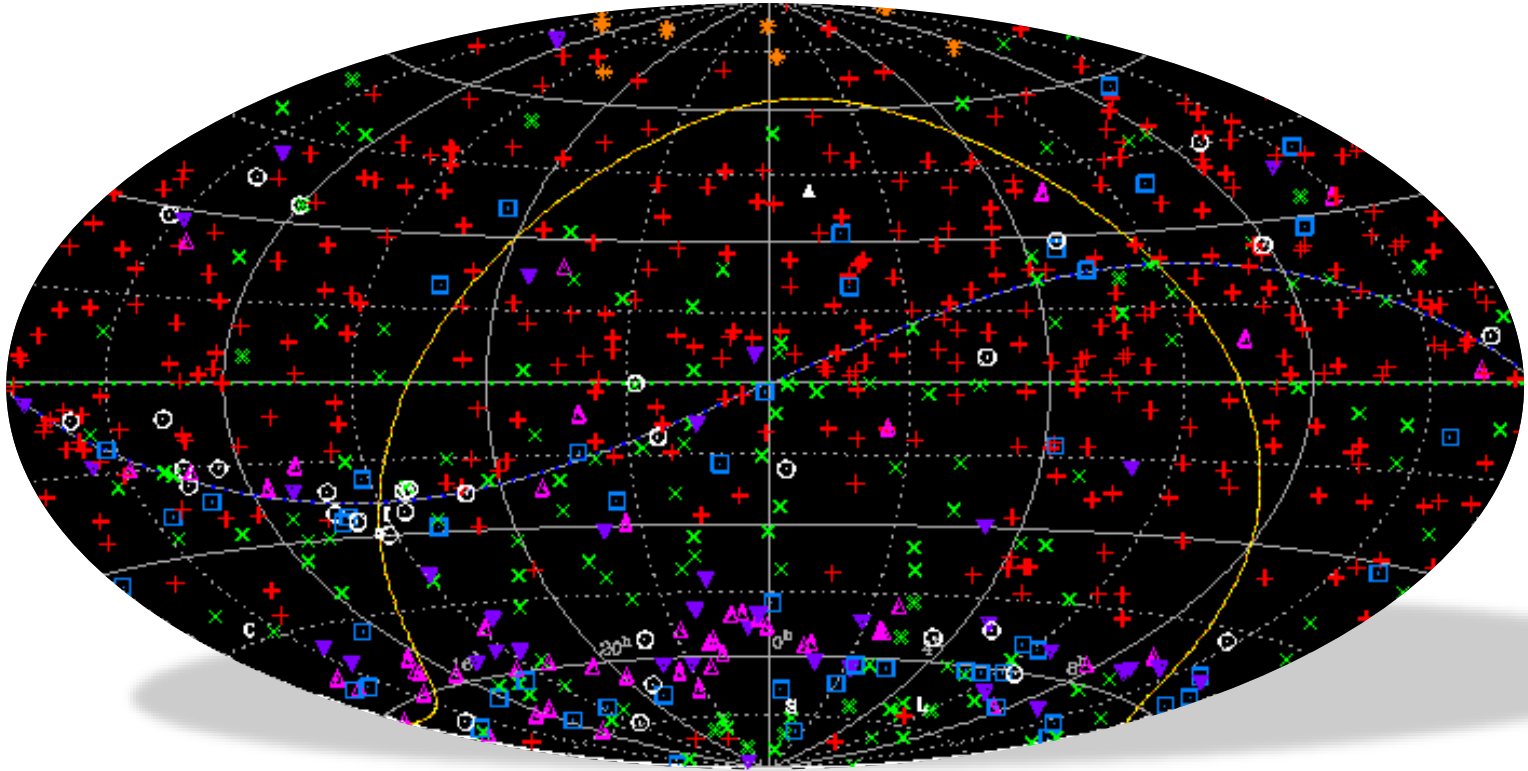




IVS General Meeting, Longyearbyen, Svalbard, Norway, 2018 June 3-9

# X/Ka Component of the Proposed ICRF-3: the importance of correlations



**Christopher S. Jacobs,** *Jet Propulsion Laboratory, California Institute of Technology*

C. Garcia-Miro, S. Horiuchi, L. Snedeker, J.E. Clark, M. Mercolino,

I. Sotuela, L.A. White



# Why build a Celestial Reference Frame at X/Ka?

- Spacecraft are allocated three frequencies: S (2 GHz), X (8 GHz), Ka (32 GHz)
- S-band usefulness is decreasing rapidly
  - Very few new missions at S-band
  - RFI at S-band is degrading the band (Wi-Fi etc.)
  - Source structure worse at low frequencies
  - Plasma calibrations much more difficult at low frequencies
- X-band is now the “workhorse” frequency
  - Source structure worse at low frequencies
- Ka-band advantages:
  - More bandwidth: 500 MHz allocation for spacecraft tones and
  - Higher telemetry rates
  - Solar plasmas effect reduced as  $1/\text{frequency squared}$ 
    - This allows tracking much closer to the Sun e.g. Parker Solar Probe mission
    - When optical tracking becomes operational,
      - still need capability close the Sun—exactly where Ka-band excels!

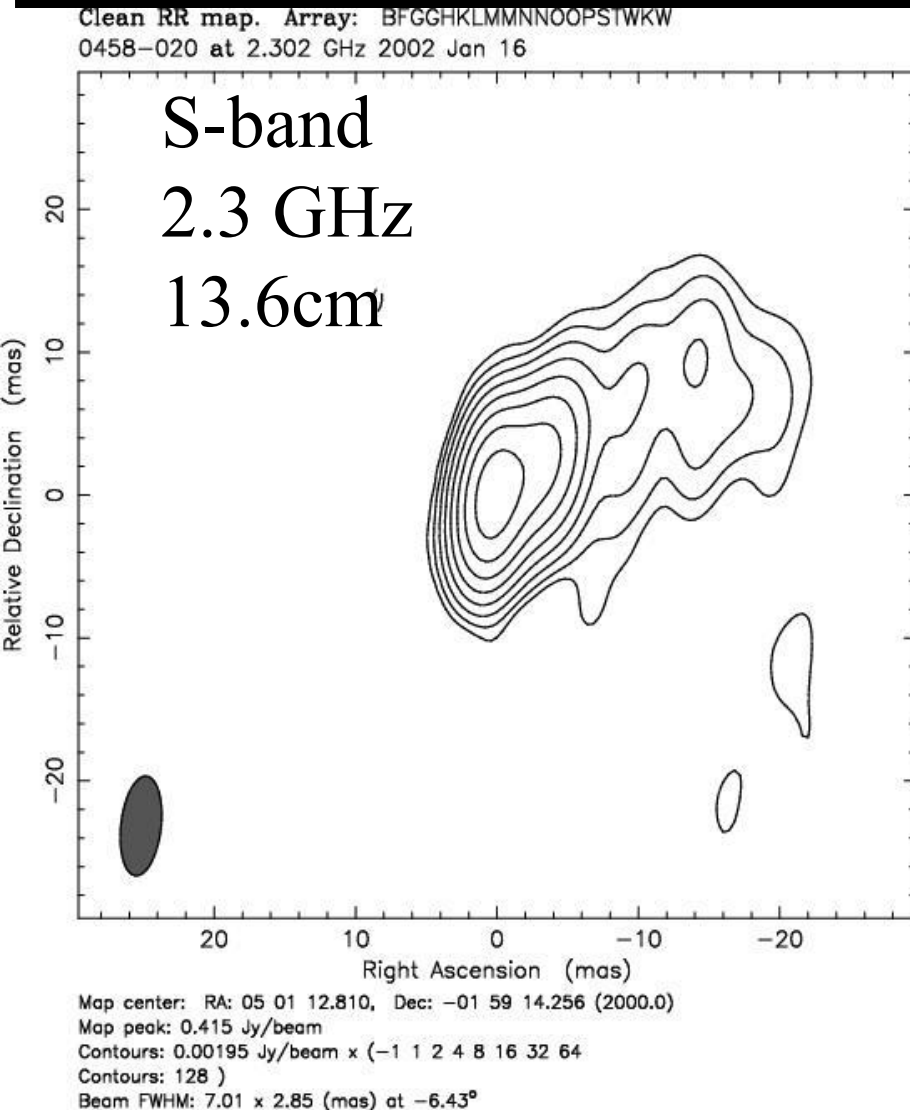


# Historical Context: Celestial Reference Frames

- Optical Frames: Used stars up through FK5 (Fricke+, 1988). Proper motions an issue. Hipparcos (Perryman+, 1997) had 100K stars mas precision but mas/yr PM precision. In late 1980s, early 1990s IAU started a move to quasars to leverage zero parallax & PM
- VLBI at SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years  
(e.g. *Ma+*, *ICRF1*, 1998, *Ma+*, *ICRF2*, 2009)
- K-band (24 GHz, 1.2cm) now sub-mas (*Lanyi+*, 2010; *de Witt+*, 2016, 2017)
- X/Ka (32 GHz, 9mm) also sub-mas (*Jacobs+*, 2016, 2017)
- Gaia optical: data release #2 is sub-mas for quasar solution (*Mignard+*, 2018)
- VLBI Accuracy limited by systematics due to weak southern geometry, troposphere, etc. at few 100  $\mu$ as



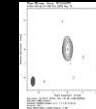
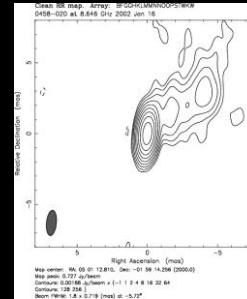
# Why Xka? Source Structure vs. Frequency



**X-band**  
8.6 GHz  
3.6cm

**K-band**  
24 GHz  
1.2cm

**Q-band**  
43 GHz  
0.7cm



**The sources  
become better →  
Less structure**

**Ka-band**  
32 GHz  
0.9cm

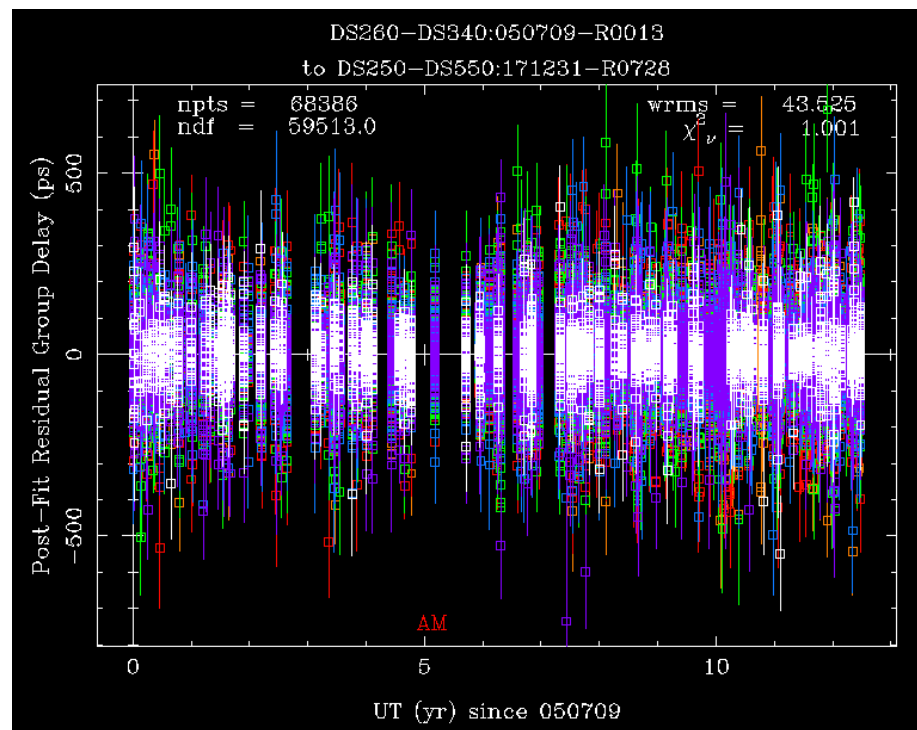
Images credit: Pushkarev & Kovalev *A&A*, 544, 2012 (SX);

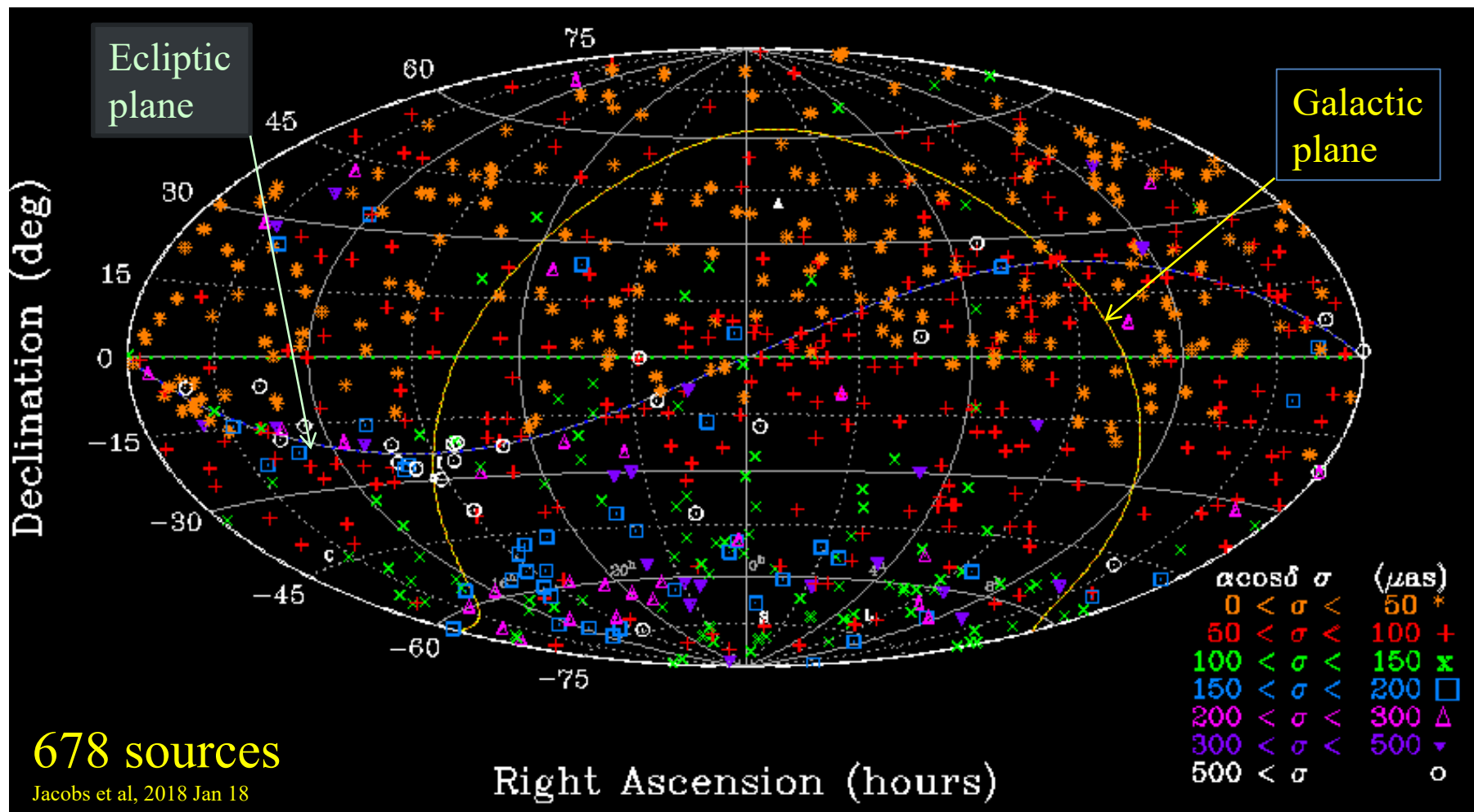
Charlot et al, *AJ*, 139, 2010 (KQ)

# Current Status of XKa Celestial Frame



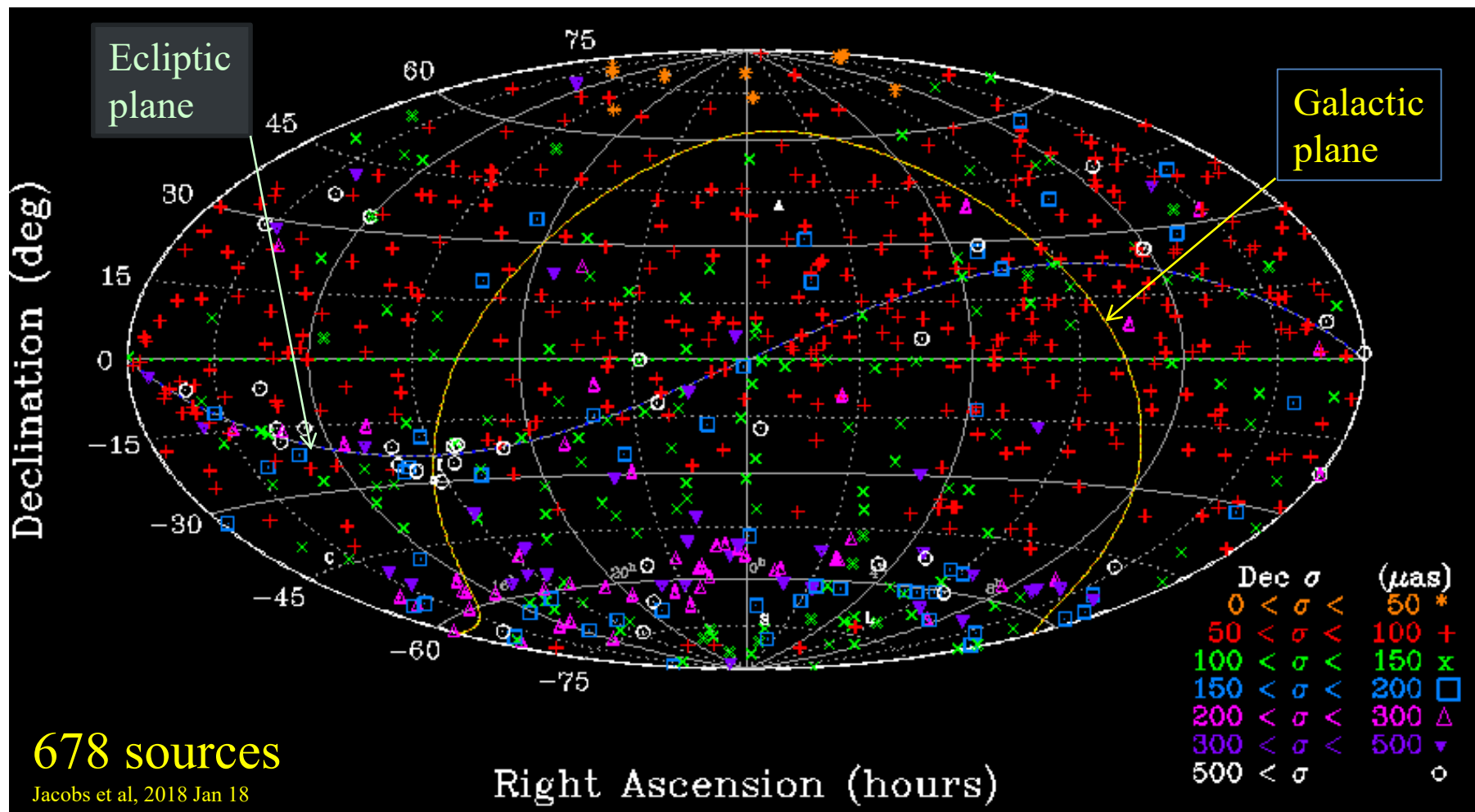
- 678 sources  
Ka-band 32 GHz, 500 MHz spanned bandwidth  
X-band 8.4 GHz, 400 MHz spanned bandwidth
- Observed 2005 July until 2017 December  
Started at 56 Mbps in 2005  
at 2048 Mbps since 2014
- 168 single baseline sessions  
on 6 baselines  
using pairs of 34-meter  
Deep Space antennas
- 68,386 observations,  
44 psec wRMS scatter



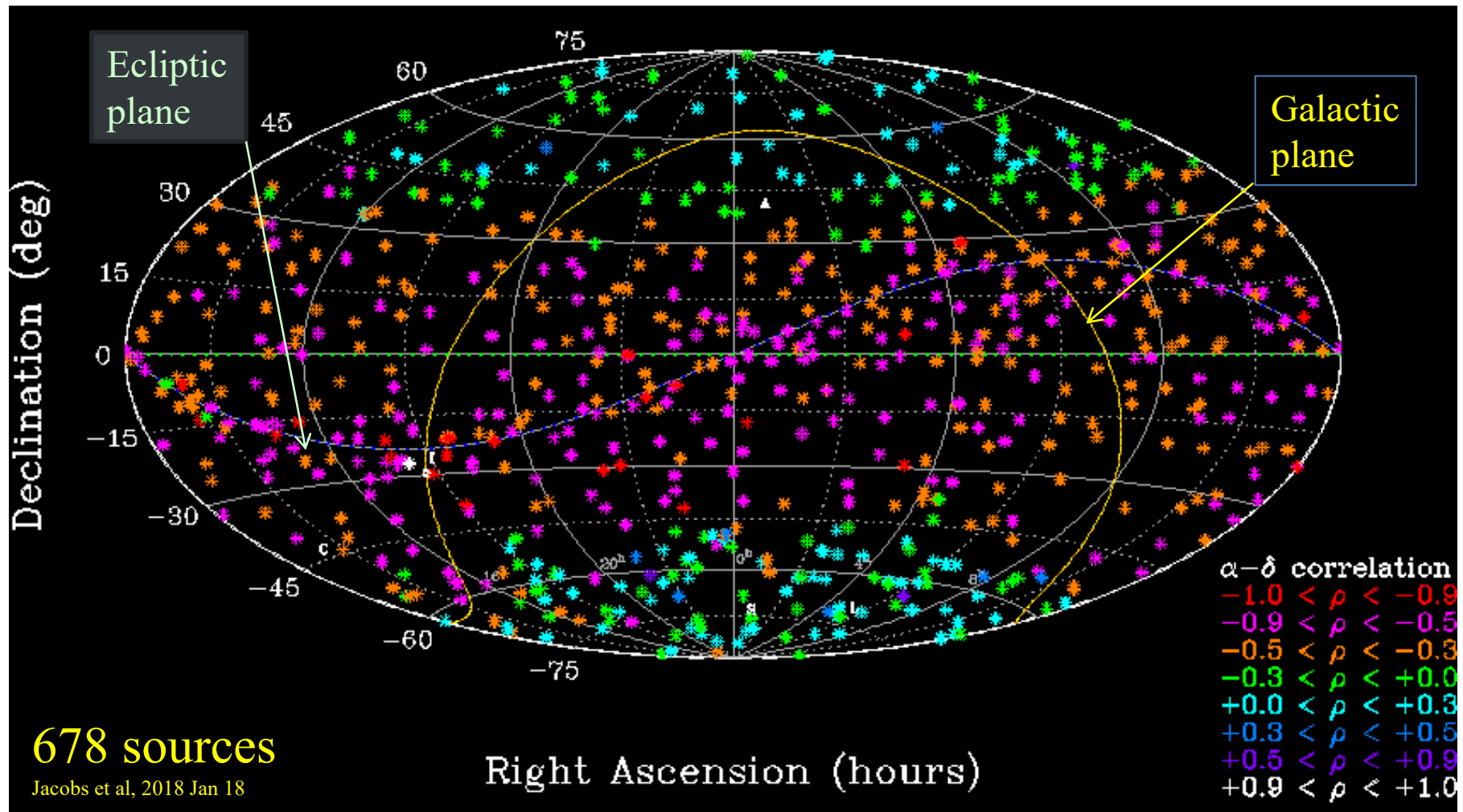


- **Strengths:**
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - needed only 68K observations vs. SX's 12 million!

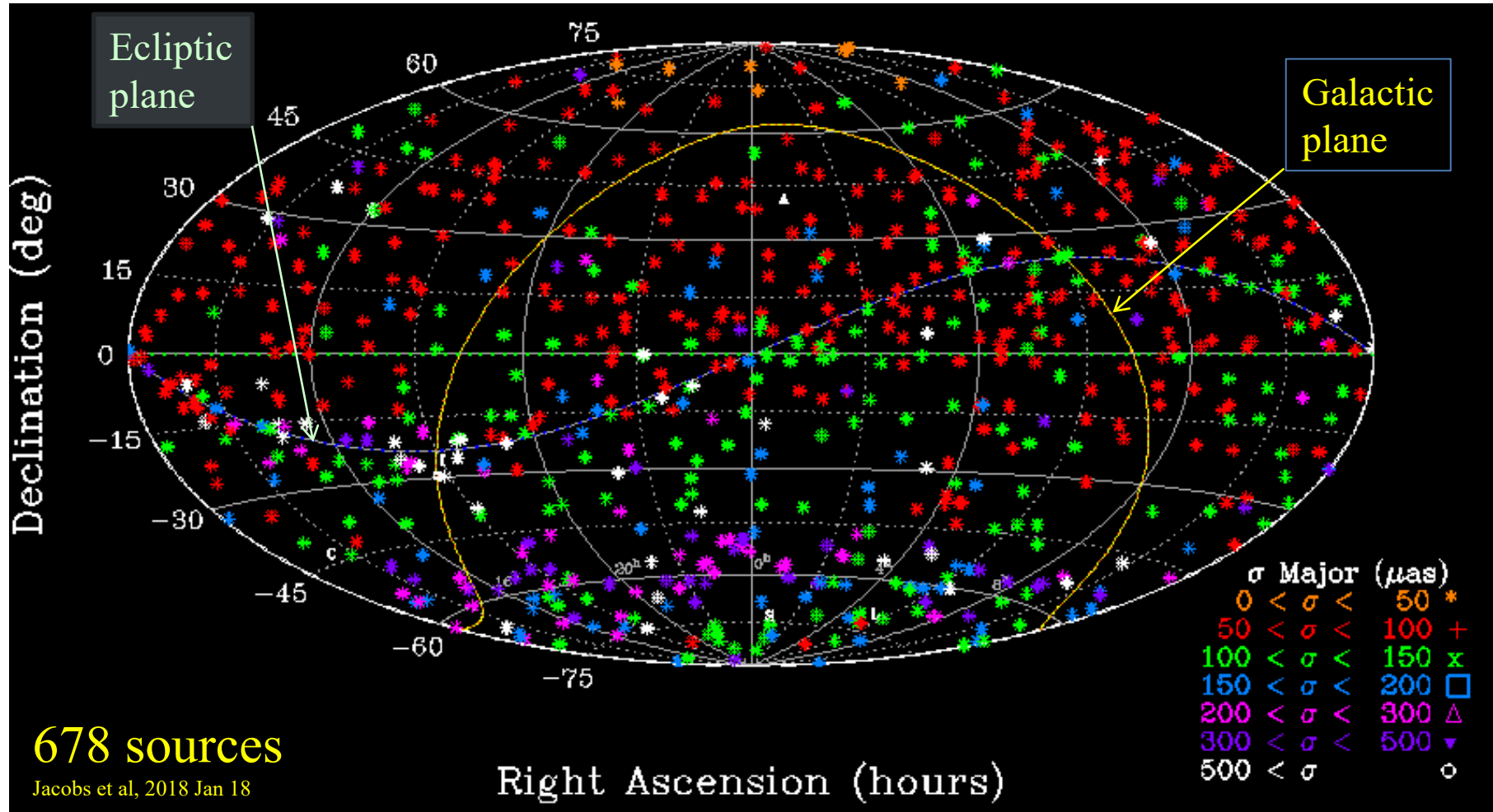
- **Weaknesses:**
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to  $\delta$  zonals
  - Limited Argentina-Australia weakens  $\delta$  from -45 to -60 deg



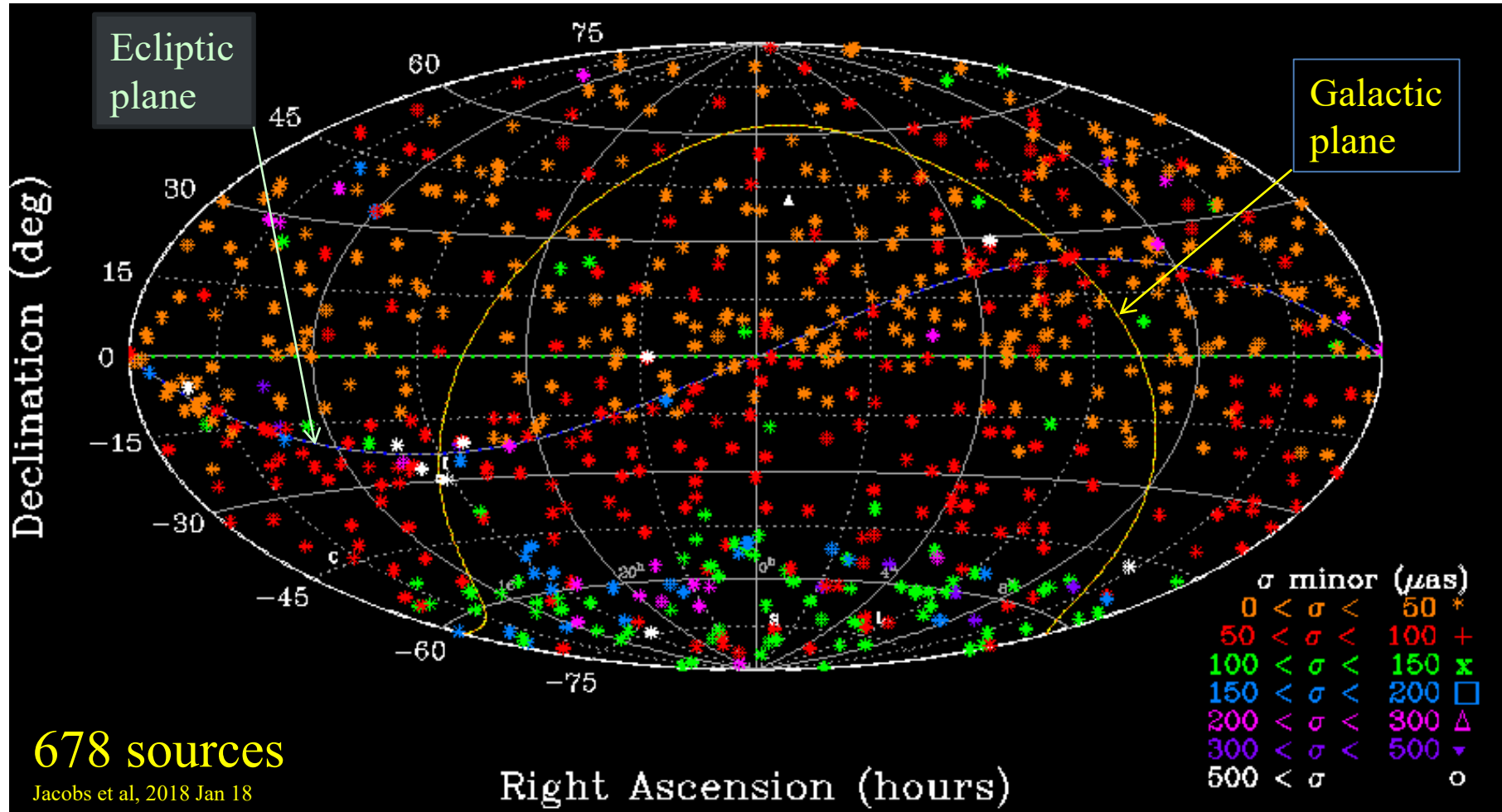
- Declination precision  $\sim 2$  times worse than RA precision
- Especially weak in southern ecliptic and far south



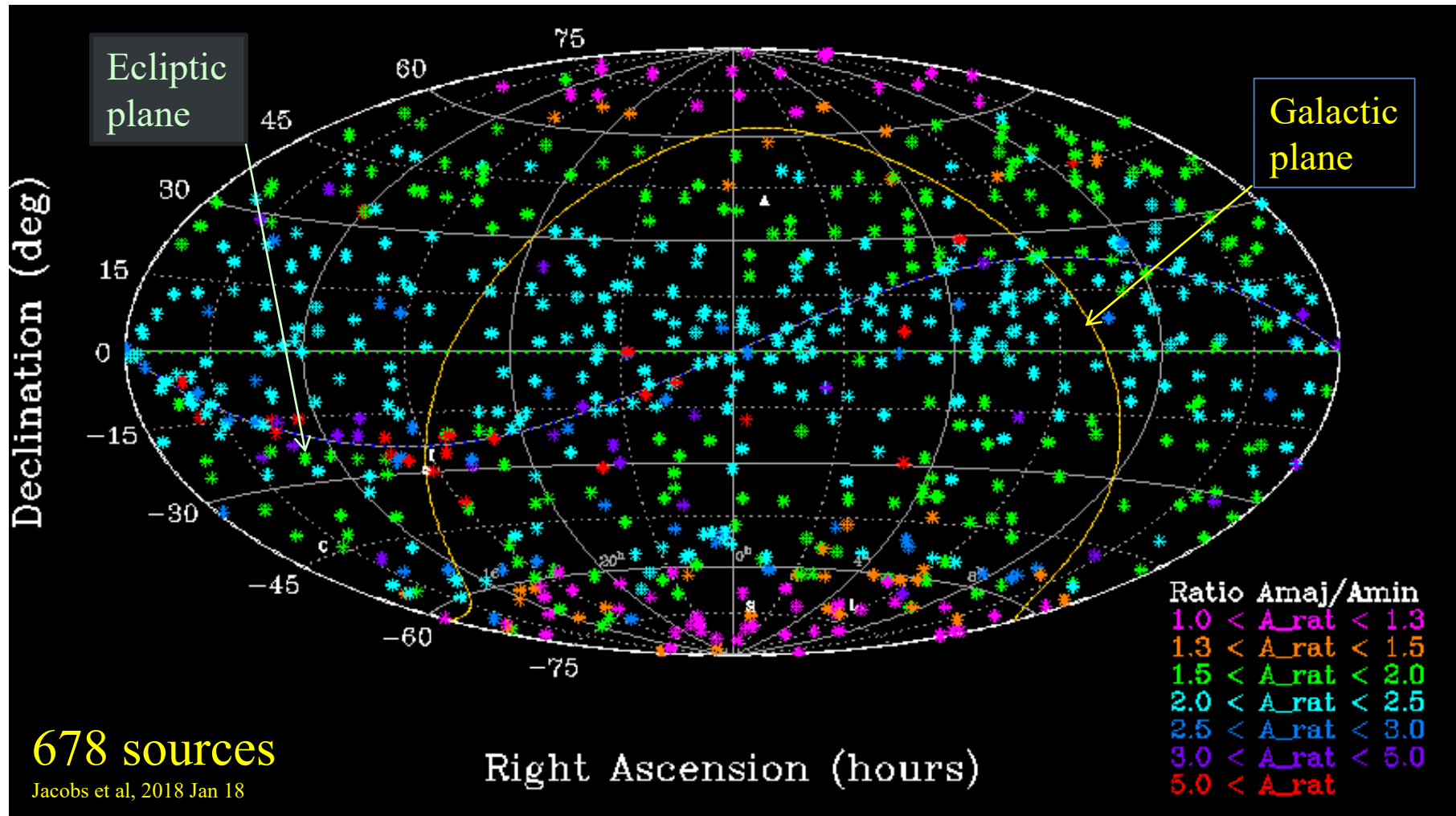
- Mid Declinations dominated by Goldstone-Tidbinbilla baseline
- Need more observations on a 2<sup>nd</sup> non-parallel North-South baseline



- Major axis shows precision in weak direction
- Major axis 2-3 times worse than required precision.



- Minor axis shows strong (precise) direction
- Meeting precision requirement in North but not south ecliptic



- Ratio  $A_{\text{maj}}/A_{\text{min}}$  shows how elongated ellipse is.
- Error ellipses typically asymmetric by factor  $\sim 2$
- Southern Ecliptic is worse by a factor of 3-5 or more



# Ka-band combined NASA/ESA Deep Space Net



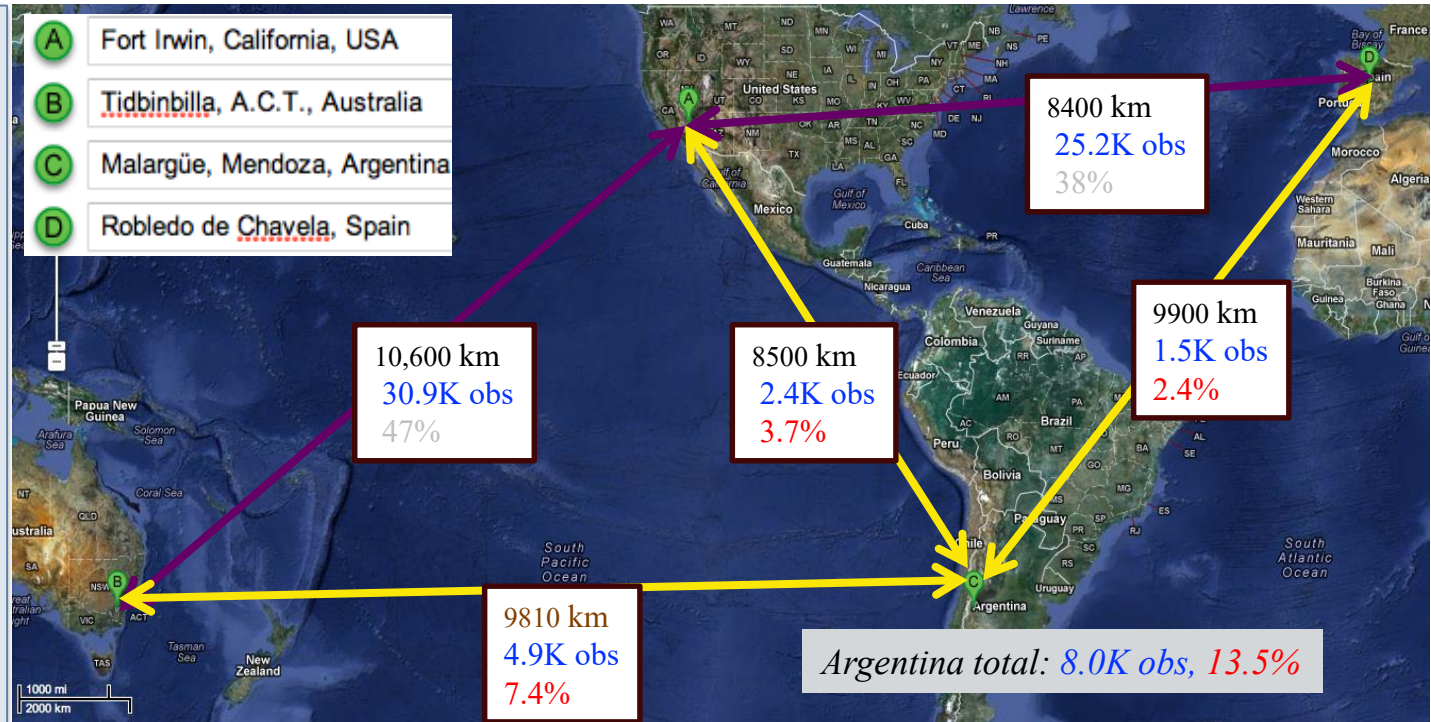
ESA Argentina to NASA-California under-observed by order of magnitude!

## Baseline percentages

- Argentina is part of 3/5 baselines or 60%  
but only 13% of obs
- Aust- Argentina 7.4%
- Spain-Argentina 2.4%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

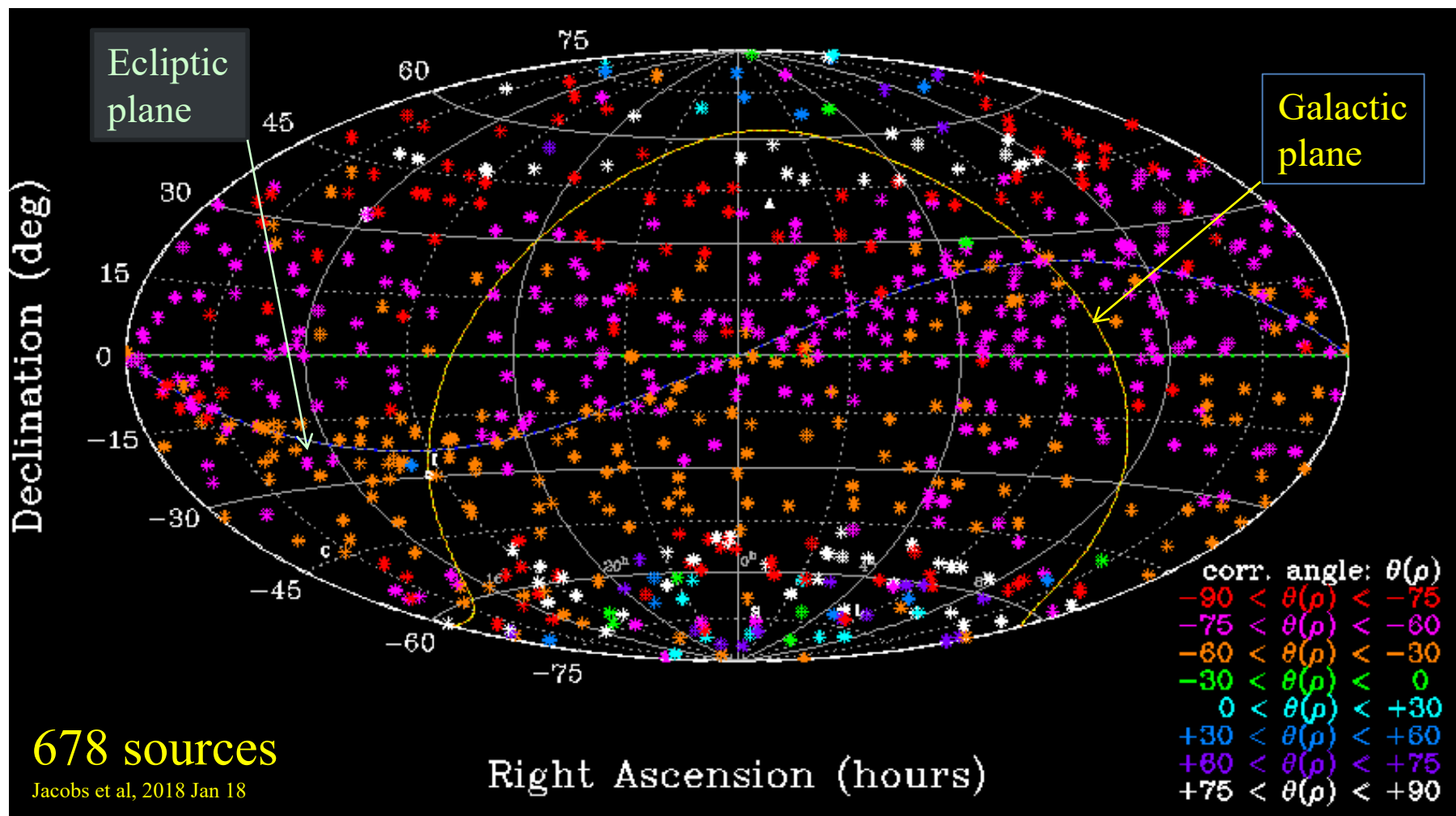
More time on ESA's Argentina station would have a huge, immediate impact!!



Maps credit: Google maps

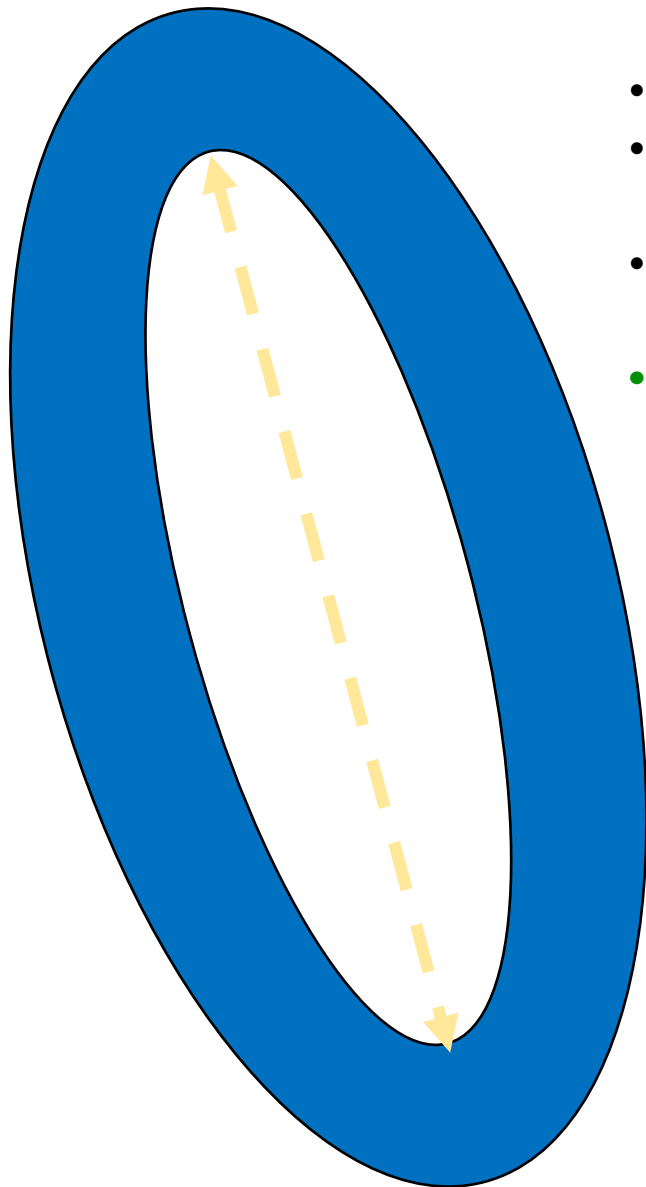
ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina



- Weak direction is close to North-South (red, magenta)
- Need North-South Baseline to correct the weakness
- In mid-south weak direction is about -45 deg (CA-Argentina)

# XKa: Typical Error Ellipse



- Major axis is  $\sim 2$  times larger than Minor axis
- Major axis direction is close to Declination direction
- **Usuda-Tidbinbilla baseline direction is a near perfect match to improve the weakest direction**
- **Goldstone-Argentina for mid-south**





# XKa vs. Gaia Optical Frame (*Mignard+*, 2018)



## Spherical Harmonic Differences for 436 common sources (10% outliers removed)

With full XKa Ra, Dec covariances

Parameter name	value	sigma	scaled $\sigma$	norm	norm+scale
R1 rotation_X	= -13.675	+ - 11.524	$\mu\text{as}$ 18.452		
R2 rotation_Y	= -16.423	+ - 12.254	$\mu\text{as}$ 19.620		
R3 rotation_Z	= 18.128	+ - 9.4607	$\mu\text{as}$ 15.148		

Dipole-1	= -20.919	+ - 15.514	$\mu\text{as}$ 24.841		
Dipole-2	= 19.055	+ - 14.950	$\mu\text{as}$ 23.937		
Dipole-3	= -191.15	+ - 49.778	$\mu\text{as}$ 79.703	-3.8 $\sigma$ , -2.4 $\sigma$	

Quad 20 Mag ( $\Delta\alpha \sim \sin 2\delta$ )= 196.04 + - 18.668  $\mu\text{as}$  29.890 10.5 $\sigma$ , 6.6 $\sigma$   
 Quad 20 Elc ( $\Delta\delta \sim \sin 2\delta$ )= 80.032 + - 25.524  $\mu\text{as}$  40.868

With Diagonal covariance only

Parameter name	value	sigma	scaled $\sigma$	norm	norm+scale
R1 rotation_X	= -12.854	+ - 11.115	$\mu\text{as}$ 16.693		
R2 rotation_Y	= -11.396	+ - 10.964	$\mu\text{as}$ 16.466		
R3 rotation_Z	= 28.905	+ - 9.2949	$\mu\text{as}$ 13.960		

Dipole-1	= -14.655	+ - 10.793	$\mu\text{as}$ 16.210		
Dipole-2	= 30.601	+ - 10.363	$\mu\text{as}$ 15.564		
Dipole-3	= -289.17	+ - 10.242	$\mu\text{as}$ 15.382	-21.6 $\sigma$ , -18.8 $\sigma$	

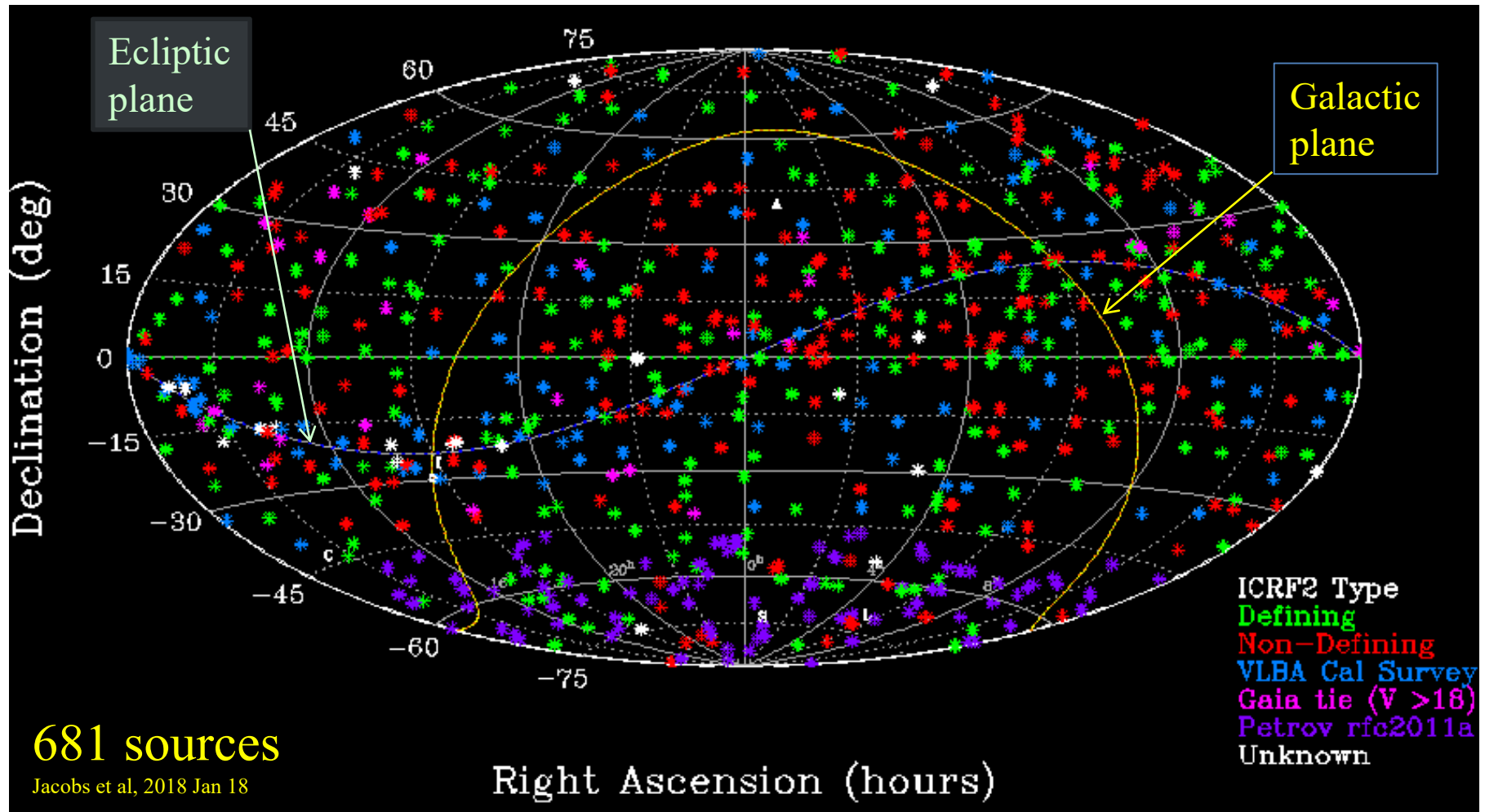
Quad 20 Mag ( $\Delta\alpha \sim \sin 2\delta$ )= 197.70 + - 10.917  $\mu\text{as}$  16.396 18.1 $\sigma$ , 12.1 $\sigma$   
 Quad 20 Elc ( $\Delta\delta \sim \sin 2\delta$ )= 145.12 + - 12.467  $\mu\text{as}$  18.724



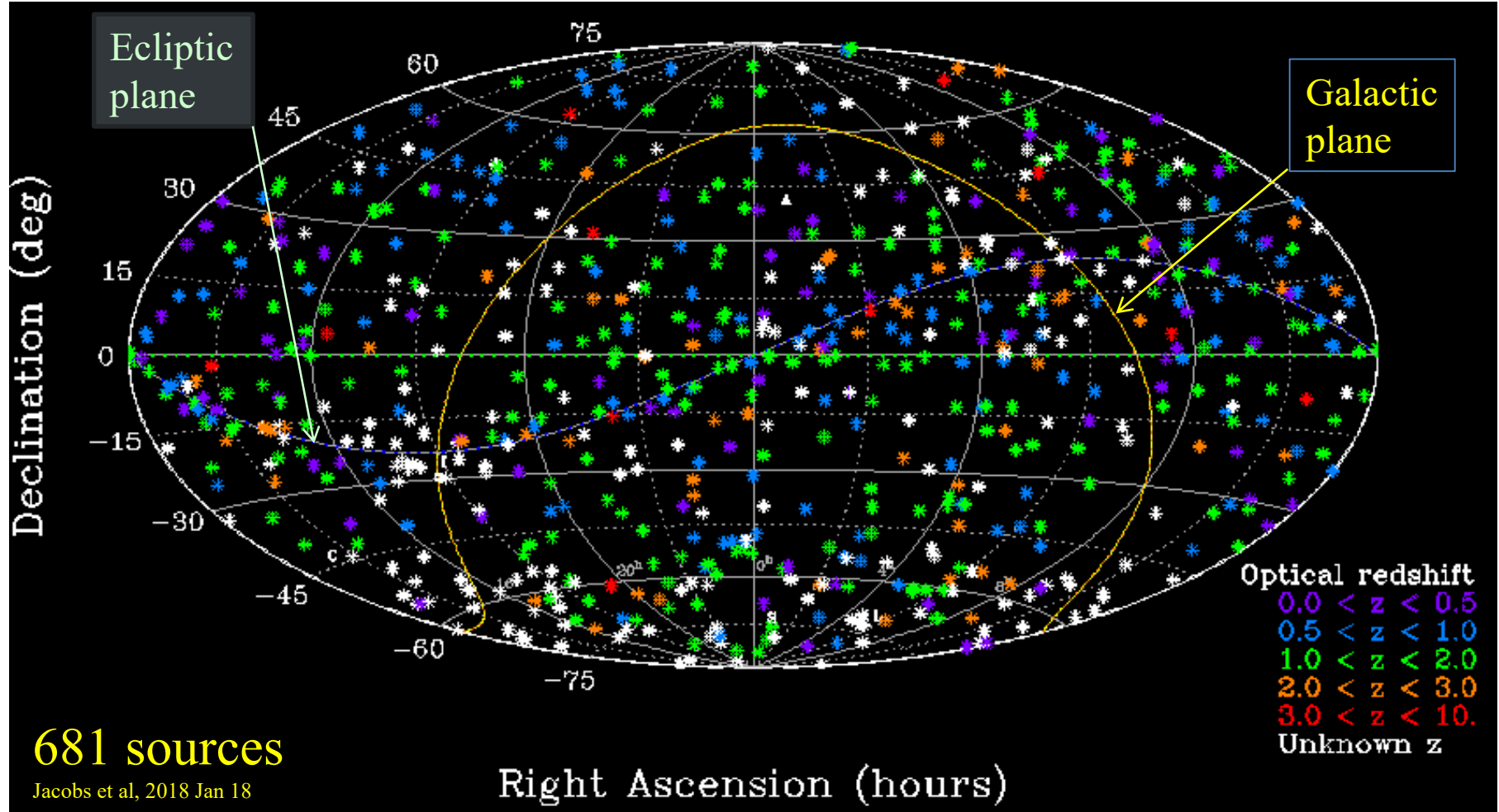
# Summary: XKa (32 GHz) Celestial Frame

- **The next International Celestial Reference Frame (ICRF-3) is under review for adoption by the IAU in August. For the first time it will include three radio wavelengths.**
- **We have reviewed the JPL XKa wavelength**
  - Full sky coverage
  - 678 sources
  - Precision  $\sim 100 \mu\text{as}$
  - Systematics: few hundred  $\mu\text{as}$
  - Under-observed baselines lead to correlations
- **Future work:**
  - Accuracy limited by systematic zonal errors vs. Declination
  - Need more Goldstone-Malargüe, Argentina data
  - Need dual-band in Argentina, Need higher data rate  $\geq 1 \text{ Gbps}$
  - **Usuda, Japan to Tidbinbilla, Australia baseline is in ideal direction!**
  - Usuda 54m can strengthen Declinations, constrain systematic zonal errors.

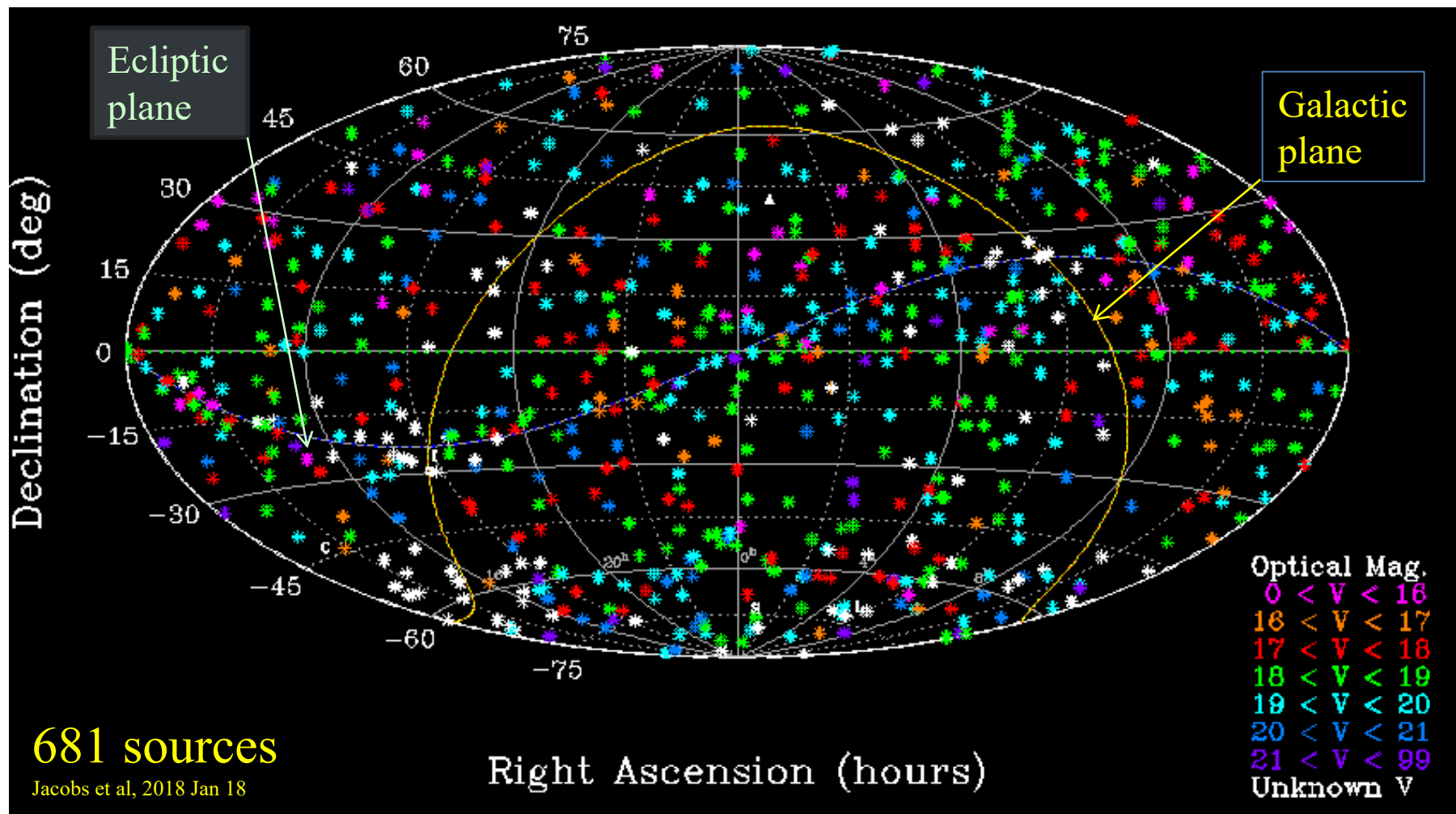
# Backup



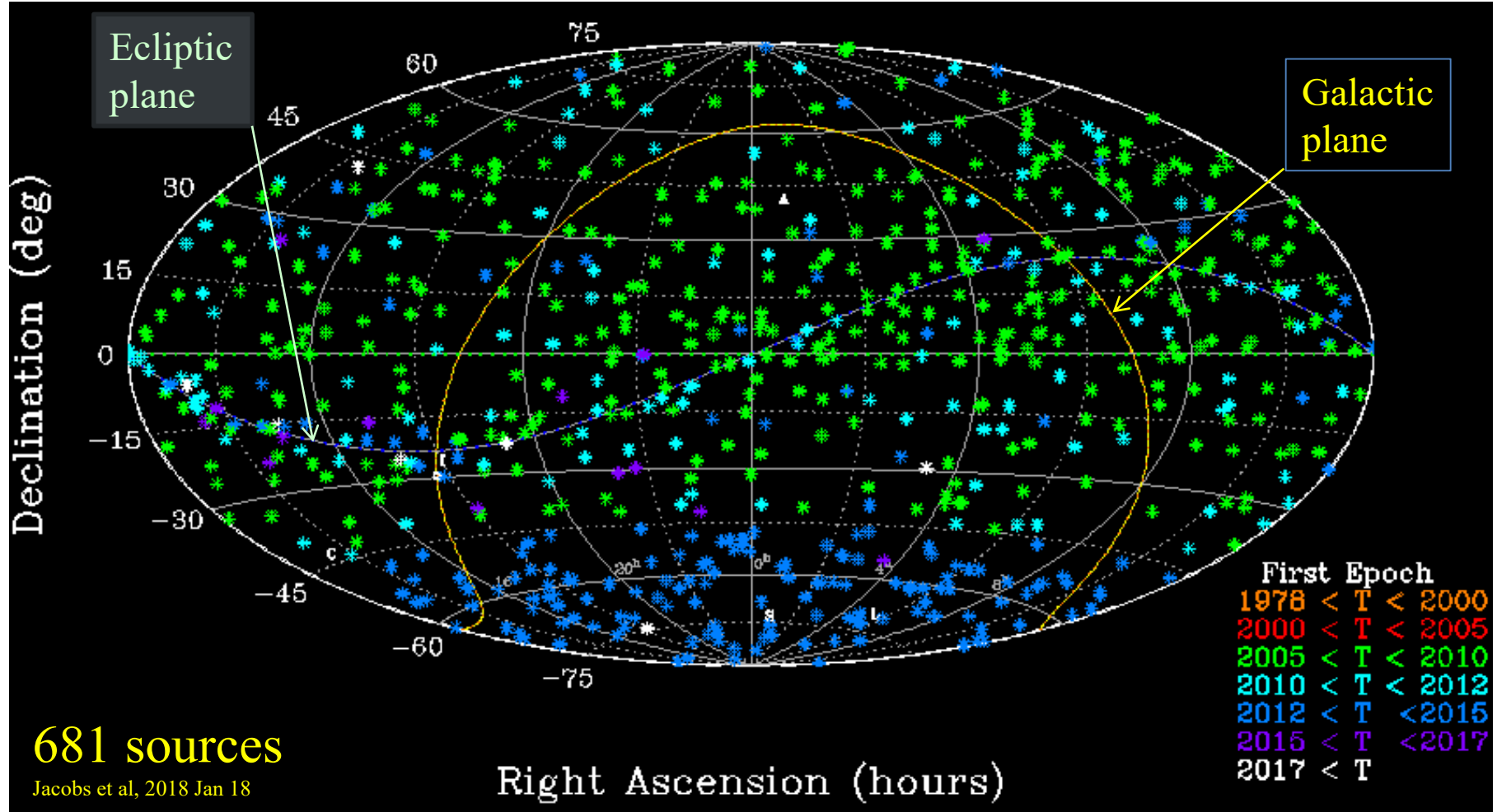
- More than 200 ICRF-2 “Defining” sources (green)
- Ensures a strong tie that aligns XKa to the ICRF-2



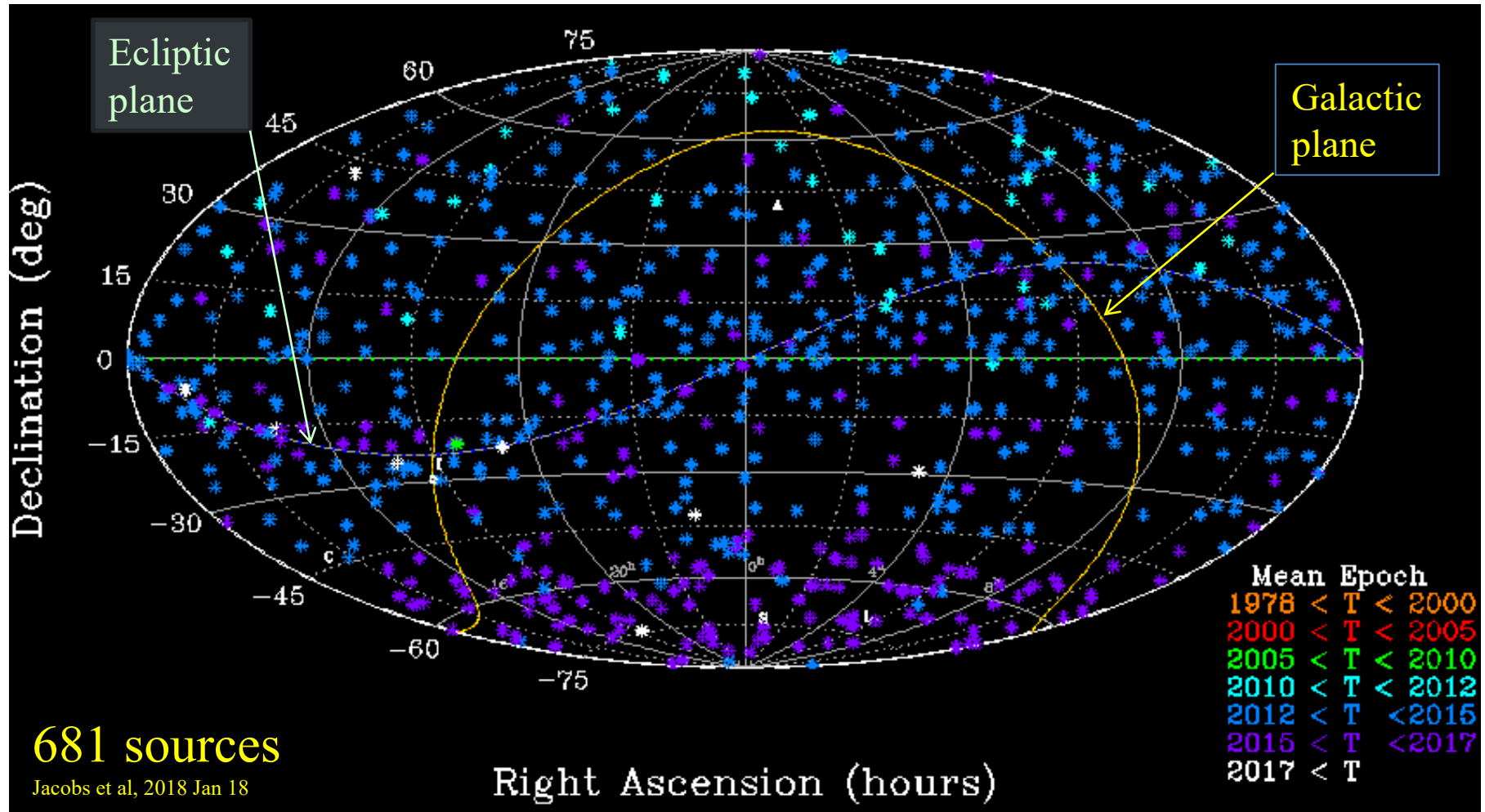
- Median redshift is  $\sim 1$  (billions of light years)
- Farthest object is  $z = 5.5$ , several objects  $z > 3$
- Allows verification of cosmological modelling



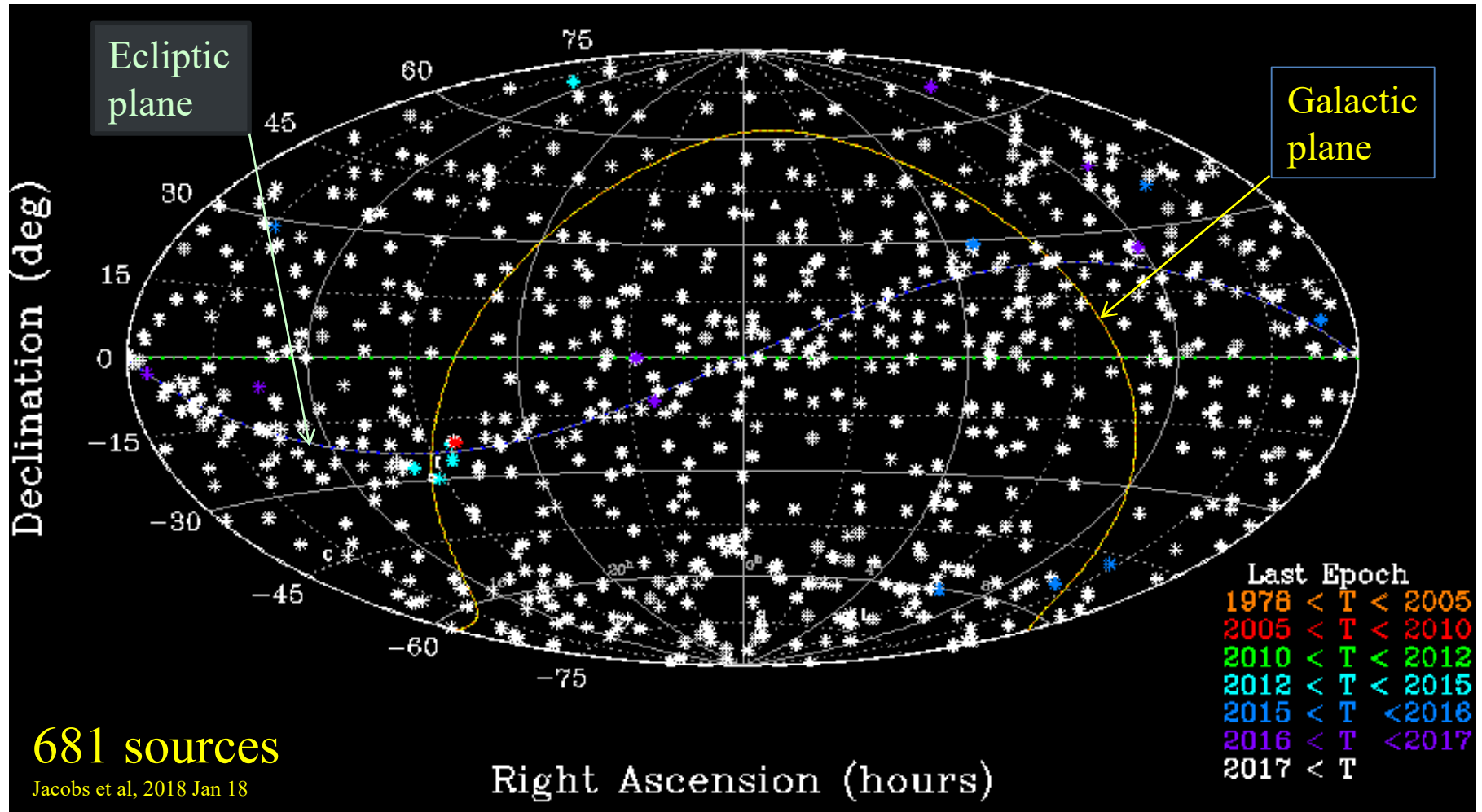
- Optical magnitudes brighter than  $V = 18^{\text{th}}$  mag allow a strong tie to the Gaia optical frame(magenta, orange, red)
- Expected tie precision  $\sim 10 \mu\text{as}$



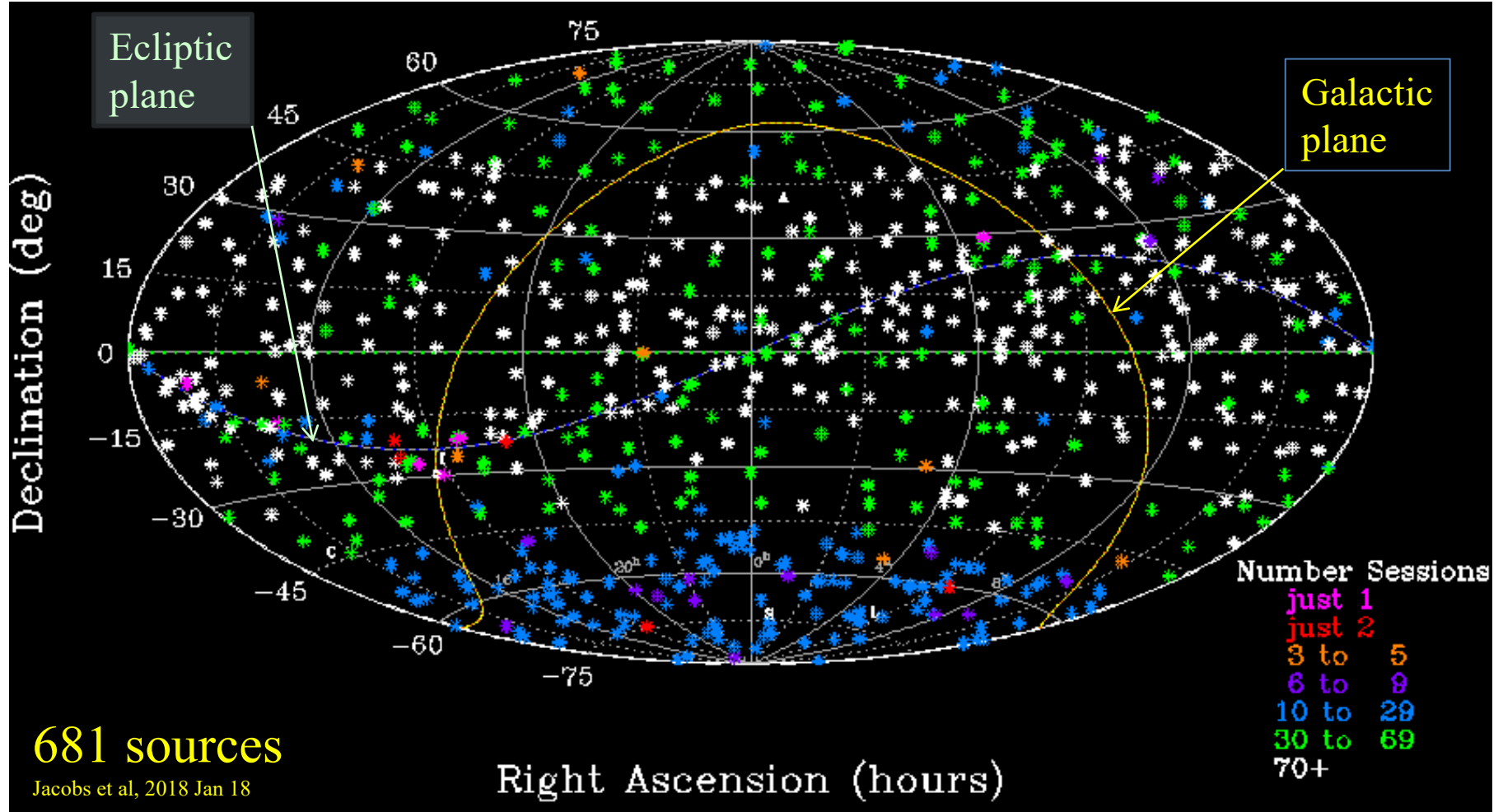
- Started in 2005 for “north” : Dec  $> -45$  deg
- Started in 2012 for far south: Dec  $< -45$  deg



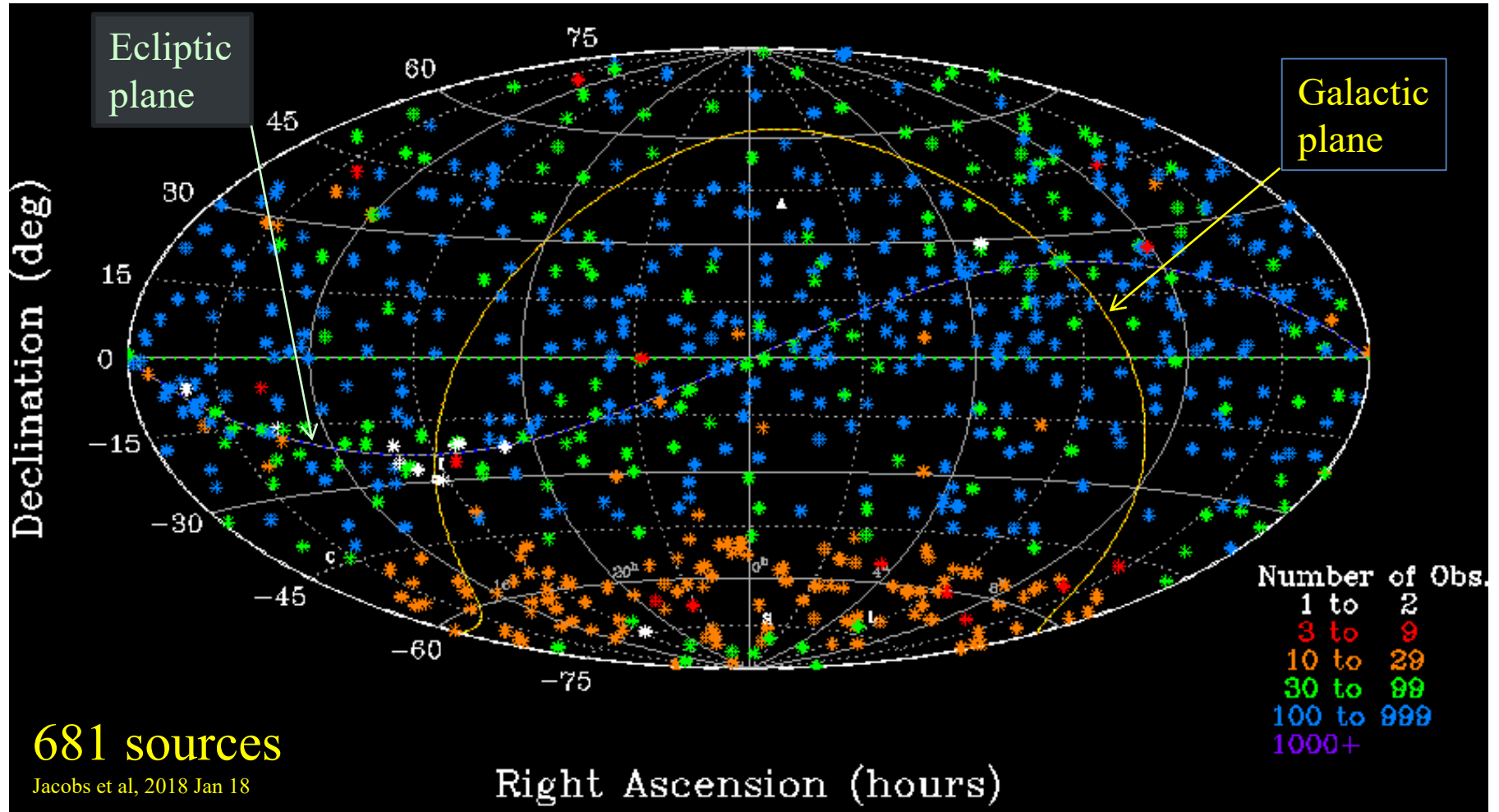
- Mean epoch of observation fairly uniform for Dec > -45 deg
- Biased toward more recent time in far south  
due to late start of Malargüe observations in late 2012



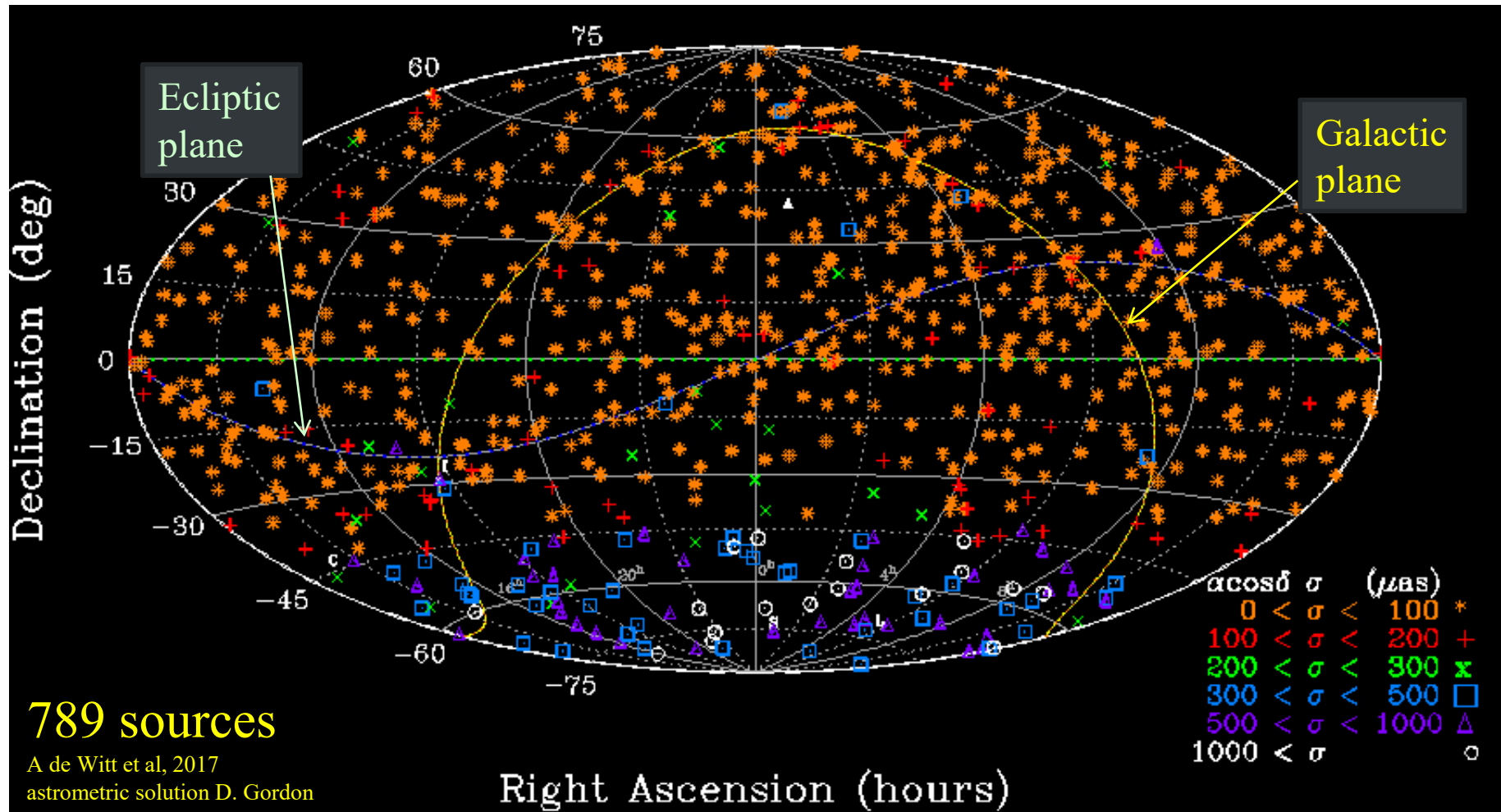
- Regular, uniform observations of all sources
- Almost all sources observed recently



- $> 70$  sessions for mid-Declinations where multiple baselines reach
- Far south now stable with  $N_{\text{sessions}} > 10$

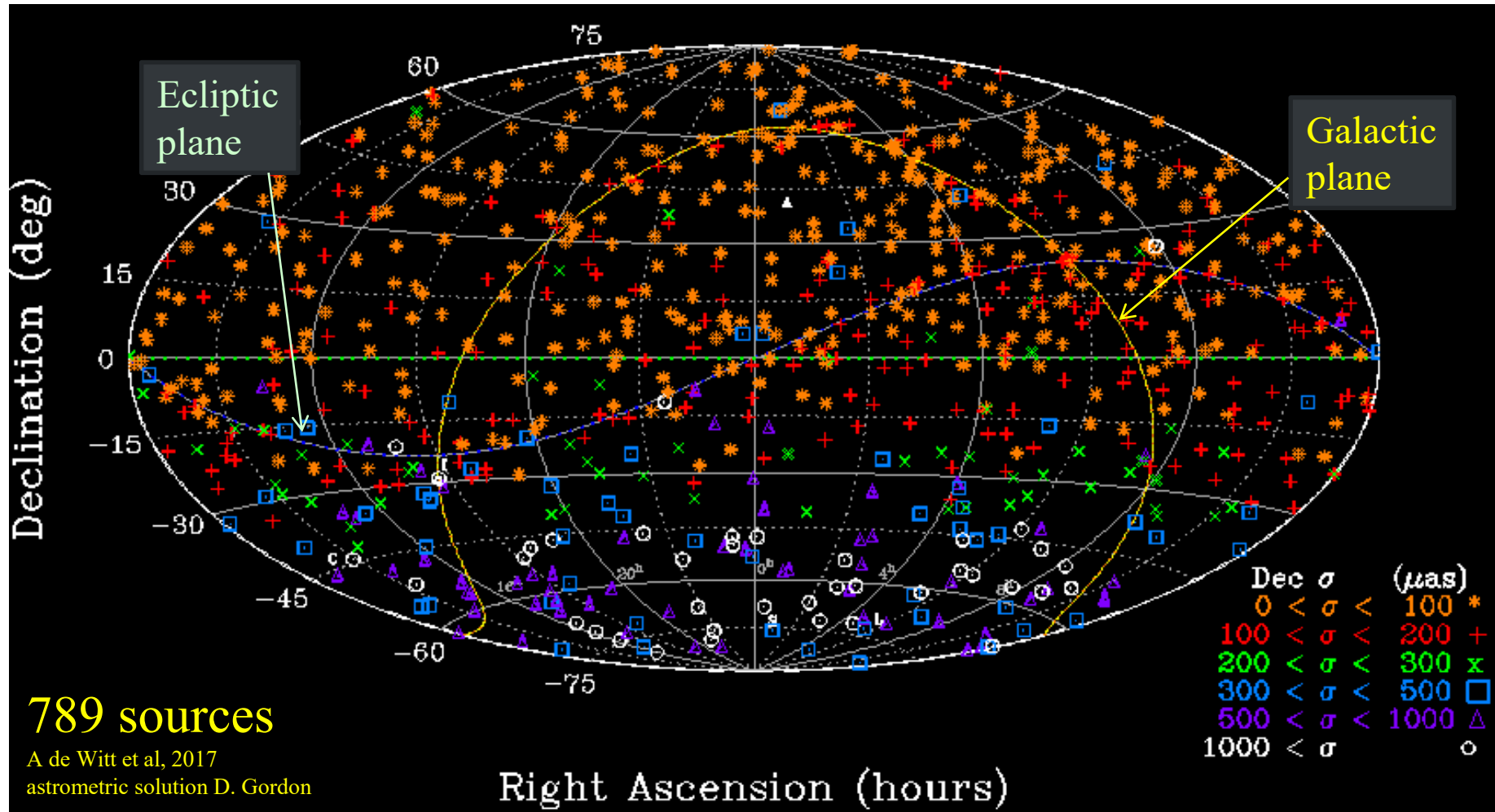


- Typically more than 100 delay observations
- Far south is 3-10 times worse



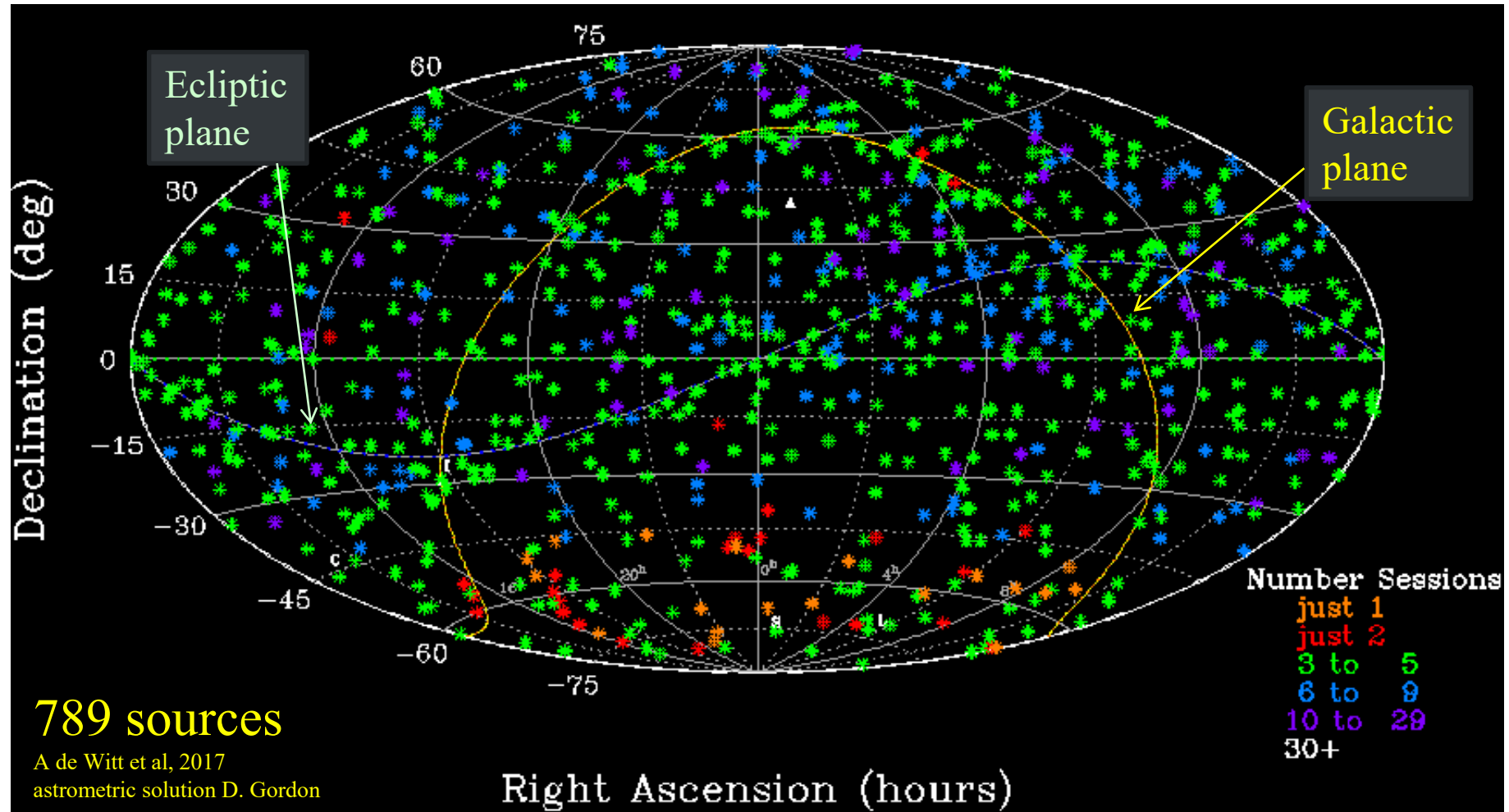
- **Strengths:**
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision  $< 100 \mu\text{as}$
  - needed  $\sim 0.25$  million observations vs. SX's 12 million!

- **Weaknesses:**
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South ( $\delta < -30$  deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data



- **Strengths:**
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100  $\mu\text{as}$
  - needed ~ 0.25 million observations vs. SX's 12 million!

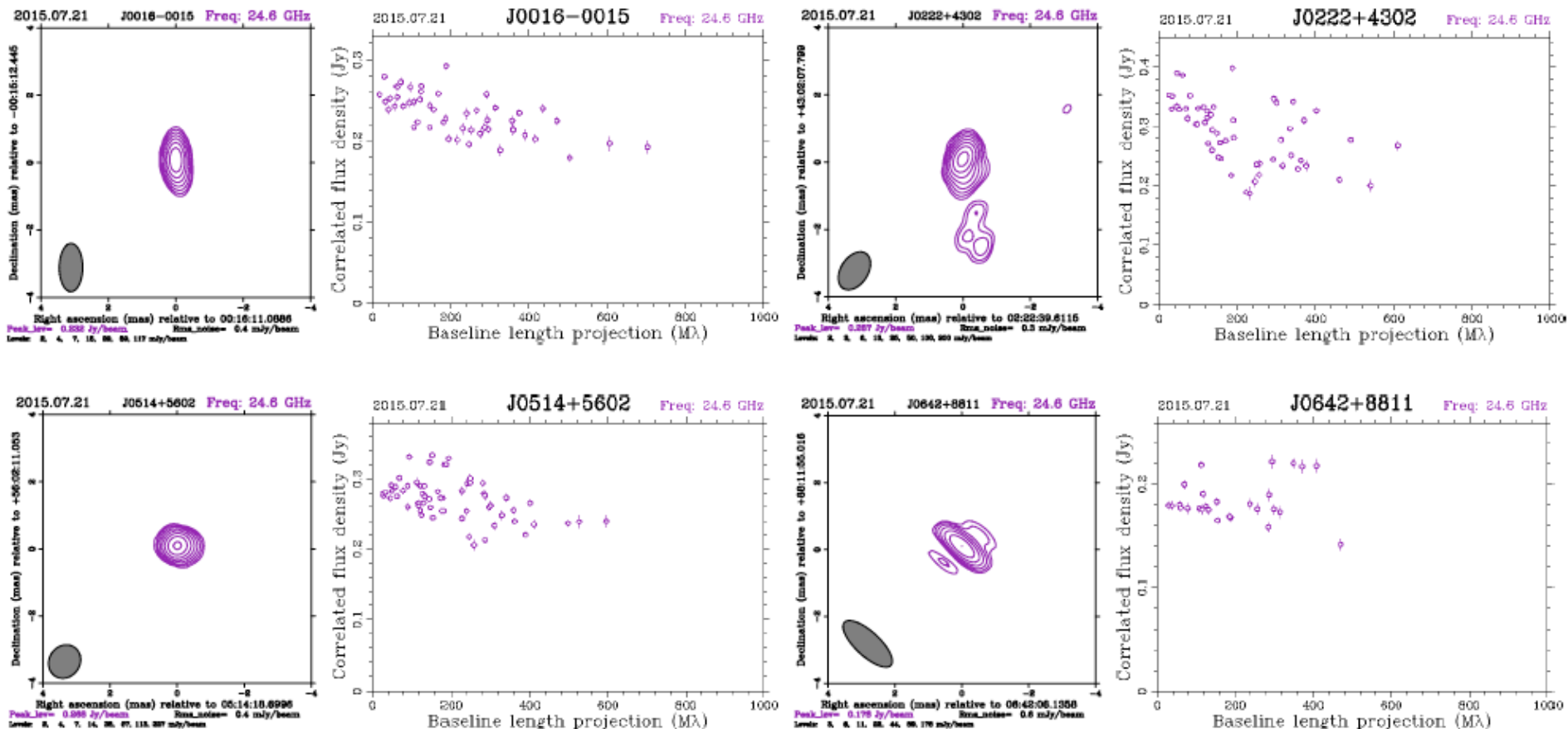
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# Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)



K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.  
Data for 500+ sources acquired. Processing limited by available analyst resources.  
Imaging will be prioritized as comparison outliers pinpoint sources of interest

# The Source Objects

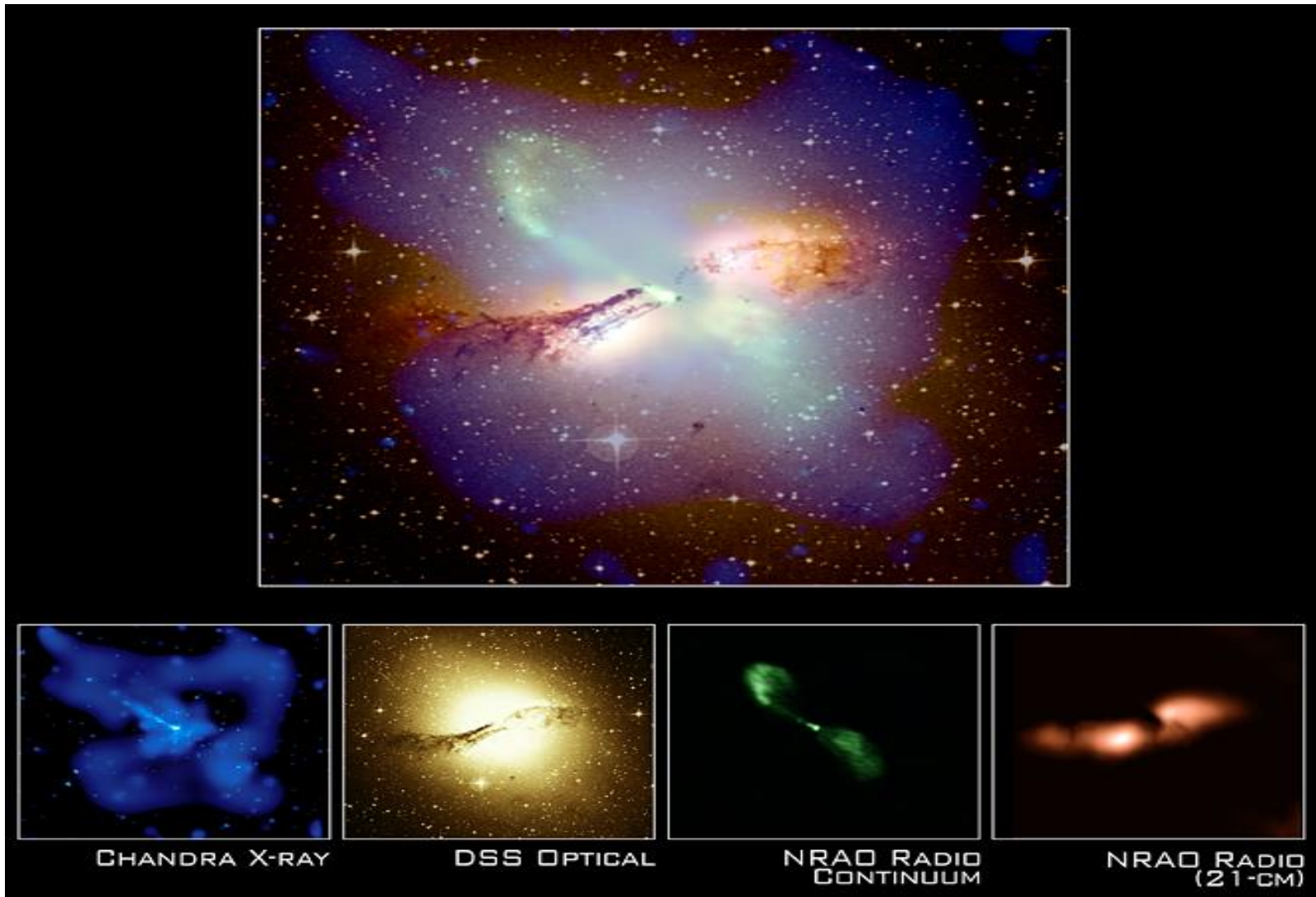
# What objects can we use?



## Methods for Tying Optical and Radio Celestial Frames

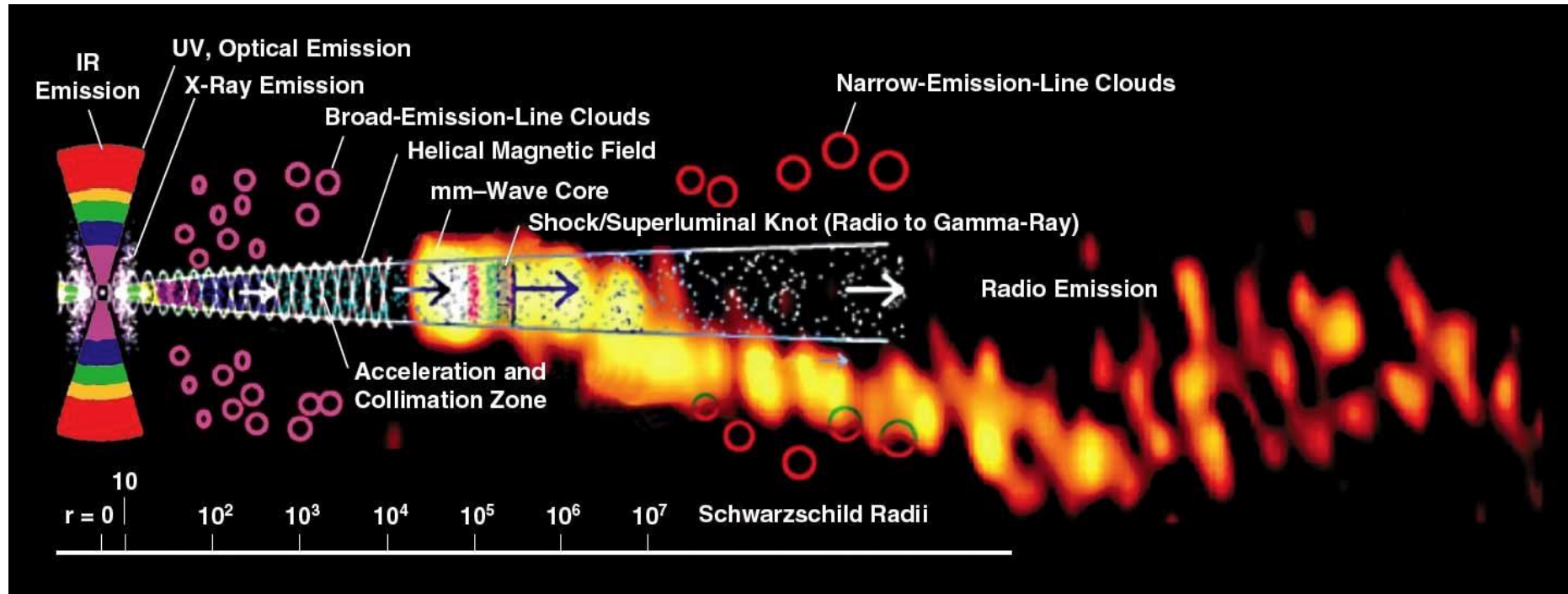
- Need common objects well measured in both optical and radio
- **Radio stars:** Previous generation used galactic stars that emit in radio,  
**Crude by today's standards: difficult to achieve desired accuracy level.**  
e.g. Lestrade et al. (1995) used radio stars to tie Hiparcos & VLBI.
- **Thermal emission from regular stars:**  
350 GHz astrometry using Atacama Large Millimeter Array (ALMA)  
Fomalont et al. (pilot observations)  
Verifies bright end of optical, **but likely limited to 500 – 1000  $\mu$ as (2.5 to 5 ppb).**
- **Extra-galactic Quasars:** detectable in both radio and optical  
potential for better than 100  $\mu$ as to 20  $\mu$ as (0.5 to 0.1 ppb).  
**Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion**

# Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),  
Radio continuum image (NRAO/VLA/J. Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

# Active Galactic Nuclei (*Marscher*)



Features of AGN: *Note the Logarithmic length scale.*

“Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core.”

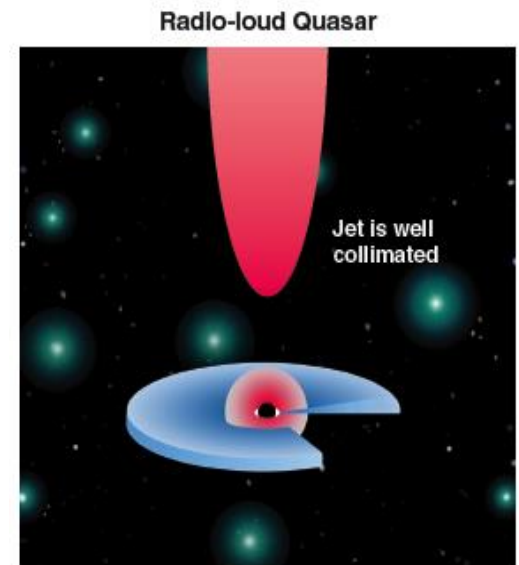
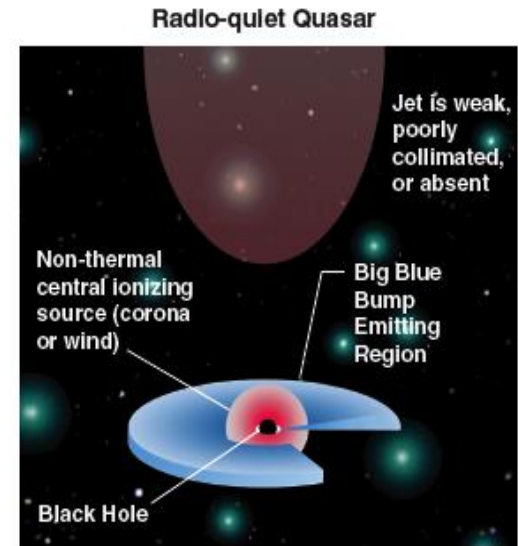
*Credits: Alan Marscher, 'Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science, VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)*



# Optical vs. Radio positions

Positions differences from:

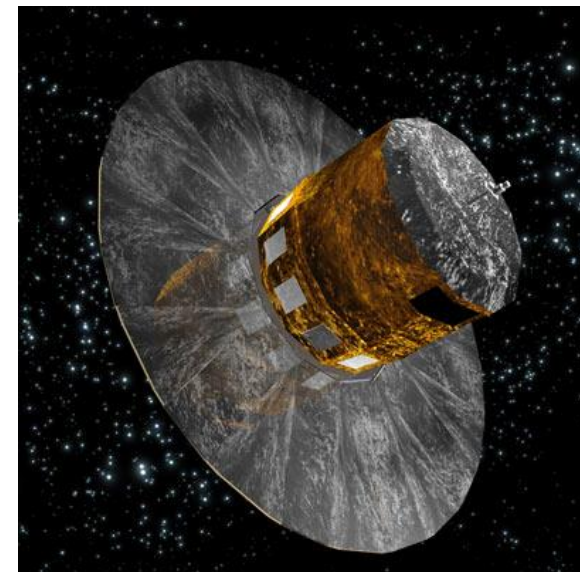
- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet?  
non-thermal ionization from corona?  
big blue bump from accretion disk?
- Instrumental errors both radio & optical
- Analysis errors



# The Gaia Optical Frame

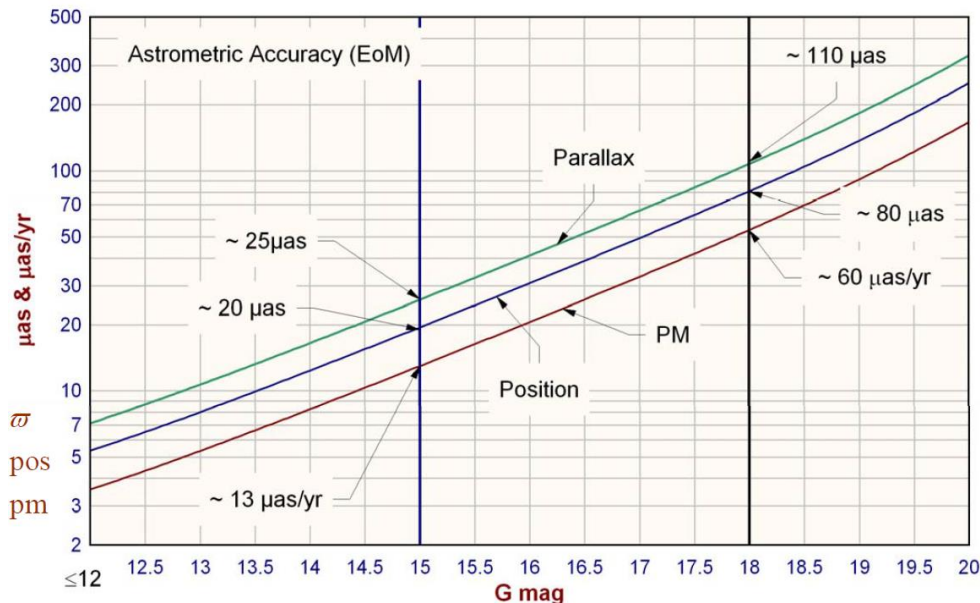
# ESA's Gaia optical Astrometry

- Method: extremely accurate centroid of 60 mas pixels. Compare to VLBI sub-mas beam.
- **Astrometry & photometric survey to  $V = 20.7^{\text{mag}}$** 
  - $\sim 10^9$  objects: stars, QSOs, solar system, galaxies.
- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects ( $V < 18^{\text{mag}}$ ) give best precision
  - 1st release Gaia astrometric catalog DR1 Sep 2016,
  - DR2 Apr 2018.



Credit: F. Mignard (2013)

## Anticipated precision of Gaia catalogue



## Gaia Data Release-1:

**$\sim 0.3$  mas in positions and parallaxes for 2 million brightest stars**

**$\sim 10$  mas for rest of the stars**

**$\sim 0.5$  mas for ICRF2 quasars (auxiliary solution)**

# Celestial Frames using Radio Interferometry (VLBI)

# Radio Interferometry: Long distance phased arrays

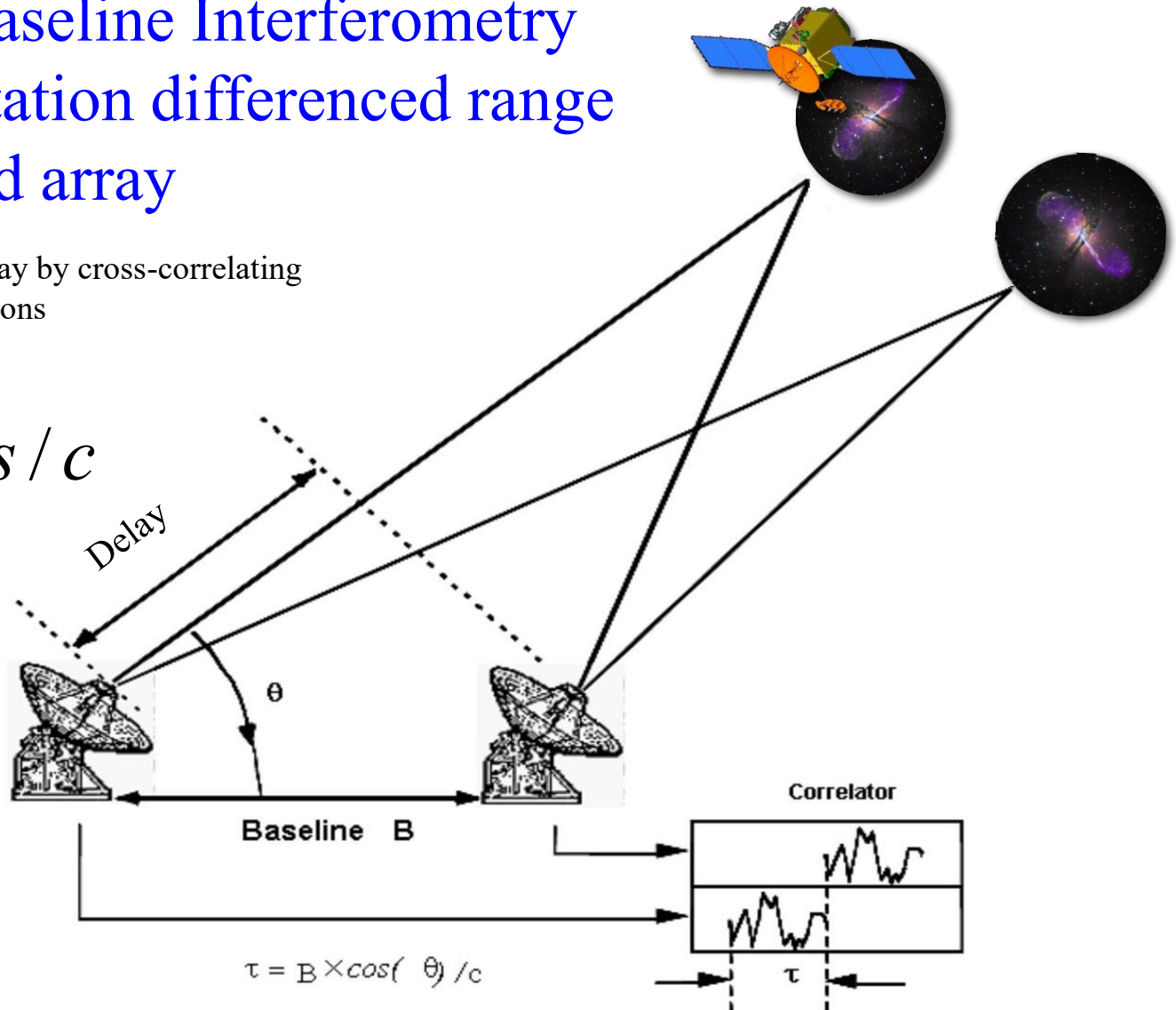
## Very Long Baseline Interferometry is a type of station differenced range from a phased array

- Measures geometric delay by cross-correlating signal from two (2) stations

$$t = B \cdot s / c$$

10,000 km baselines  
give resolution of  
 $\lambda/B \sim$  few nanoradian  
sub-mas beam !!

Resolves away all  
but galactic nucleus



The goal:

Alignment of Optical and Radio  
into Common Frame

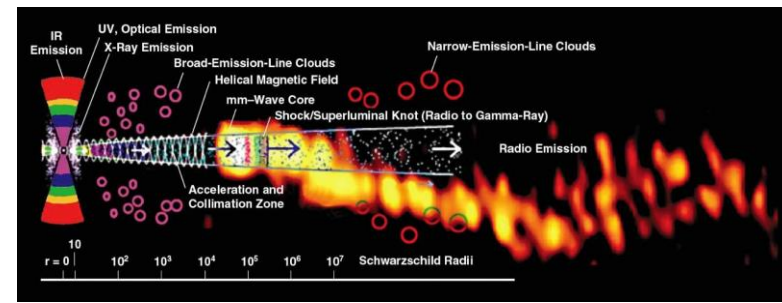
# Optical-Radio Frame Tie Geometry

Determine 3 small rotations ( $R_{1,2,3}$ ) and zonal differences i.e. spherical harmonics  $Y_{lm}$  between the individually rigid, non-rotating **radio** and **optical** frames to sub-part per billion level

Allows seamless integration into united frame.

**More than 1 billion objects will be integrated into common frame!!**

**Object precision to  $< 100 \mu\text{as}$ , 0.5 ppb. want tie errors 10 times smaller.**

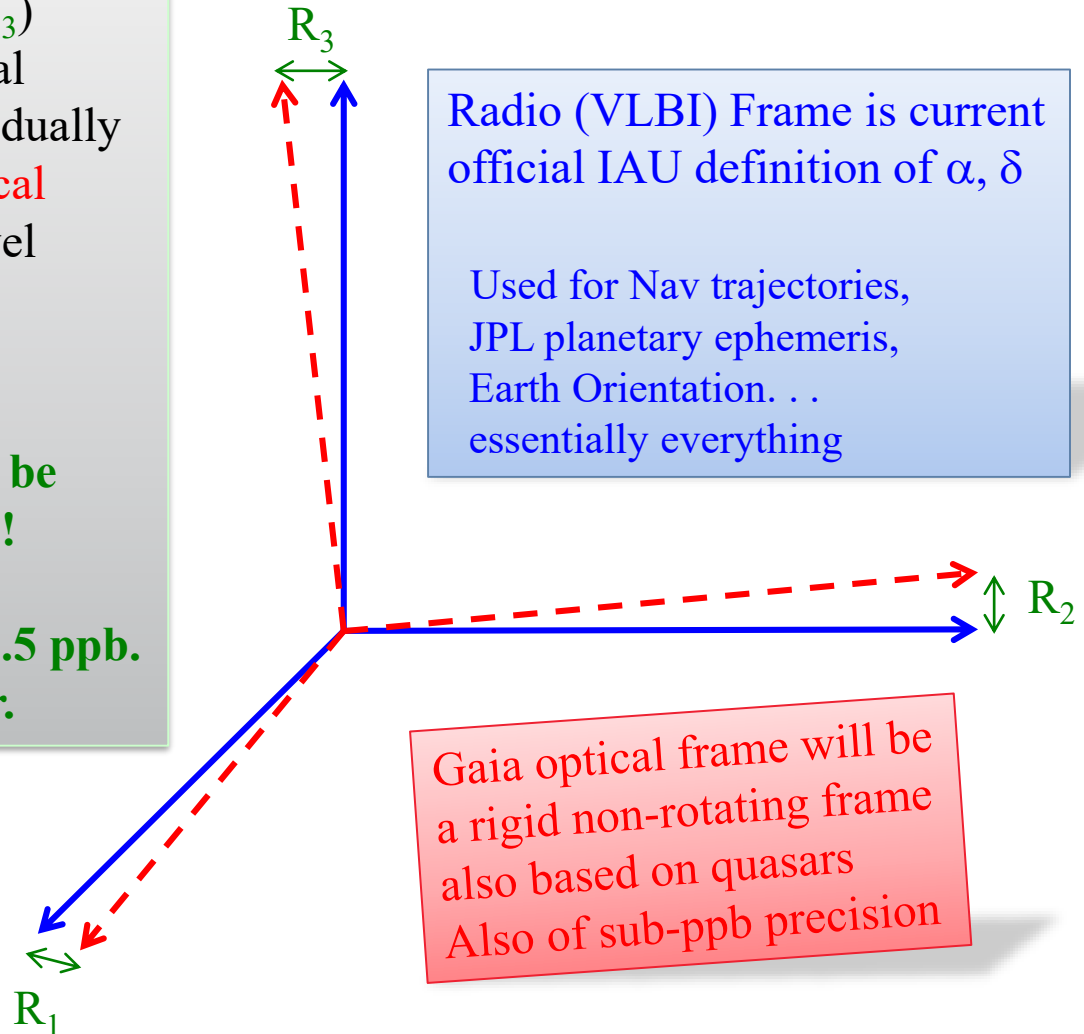


Credit: Marscher+, Krichbaum+

Radio (VLBI) Frame is current official IAU definition of  $\alpha, \delta$

Used for Nav trajectories,  
JPL planetary ephemeris,  
Earth Orientation. . .  
essentially everything

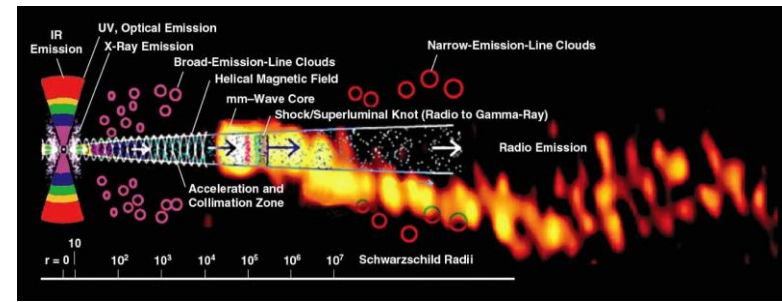
Gaia optical frame will be  
a rigid non-rotating frame  
also based on quasars  
Also of sub-ppb precision



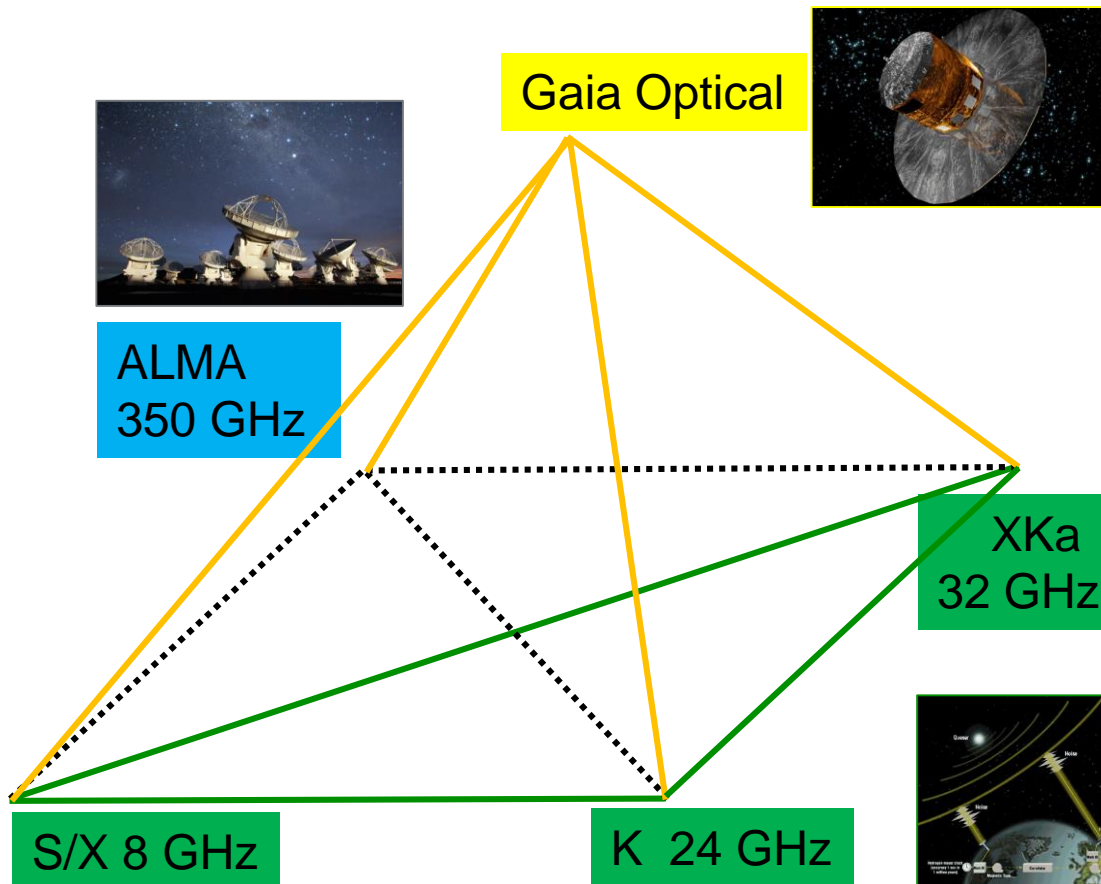
# Frame Tie Comparisons

## Tying Optical and Radio Celestial Frames

Systematics to be flushed out via  
Inter-comparison of multiple high  
precision frames.



Credit: Marscher+, Krichbaum+



### Systematics:

Gaia: 60 mas beam sees  
Host galaxy, foreground stars, etc.

ALMA: pilot obs bright end  $\sim 5^{\text{mag}}$   
Waiting on 10km+ configurations

VLBI: All bands need more  
southern data

S/X: Source structure

K: Ionosphere

XKa: Argentina baselines  
under-observed

# Tying optical and Radio Celestial Frames

## Gaia DR1-aux vs. VLBI



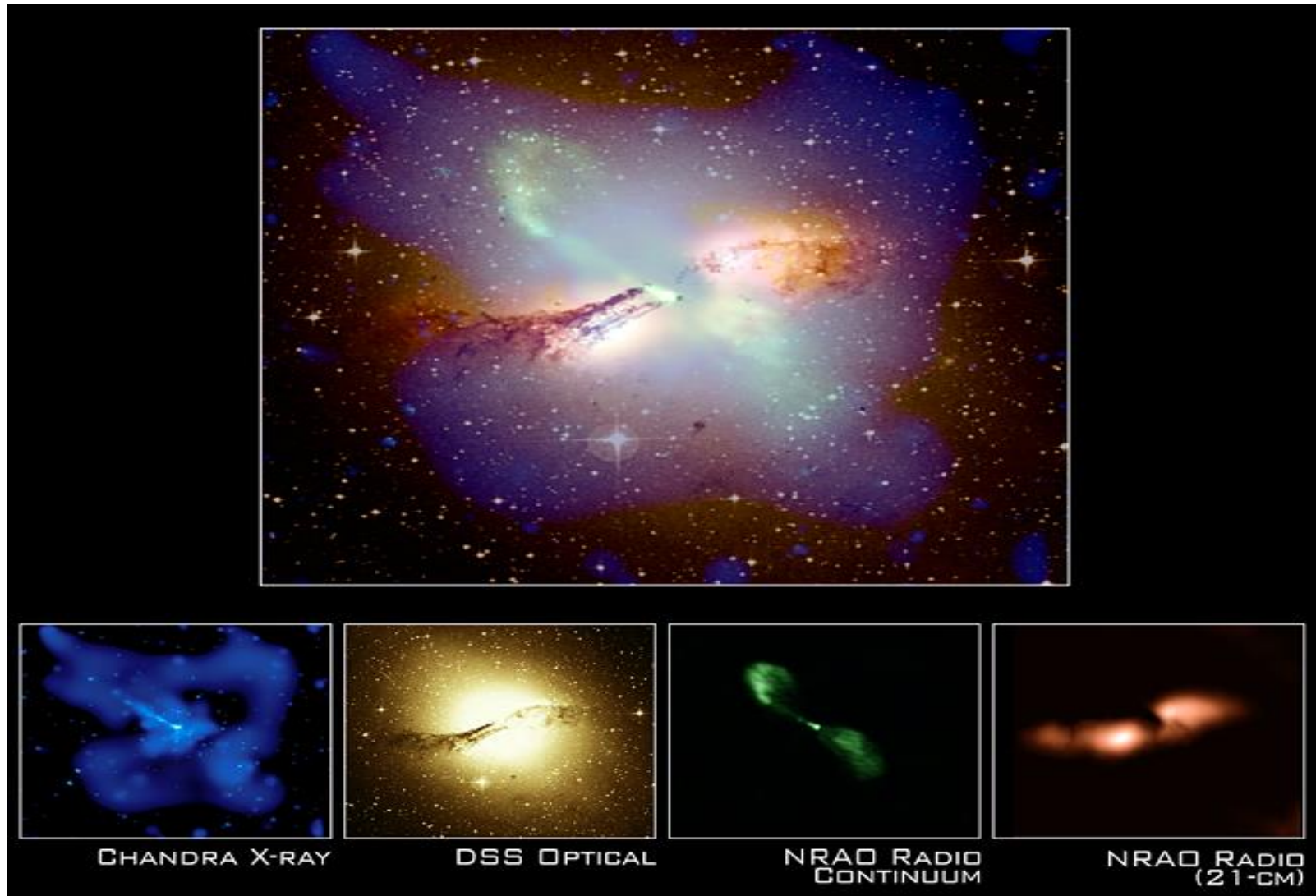
	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1926	473	405
# outliers $> 5\sigma$	100	13	6
% outliers	5.2 %	2.7 %	1.5 %
$\alpha$ wRMS	523 $\mu$ as	431 $\mu$ as	433 $\mu$ as
$\delta$ wRMS	531 $\mu$ as	453 $\mu$ as	418 $\mu$ as
$R_x$	-37 +- 13	-89 +- 24	57 +- 24
$R_y$	0 +- 11	14 +- 21	32 +- 21
$R_z$	-29 +- 13	-13 +- 23	21 +- 24
$\Delta\alpha$ vs. $\delta$ tilt ( $\mu$ as/deg)	-0.46 +- 0.25	-1.55 +- 0.53	-2.83 +- 0.58

Rx vulnerable  
To trop errors

Hints that results improve by going to higher radio frequency  
However, the above results do not use exact same objects

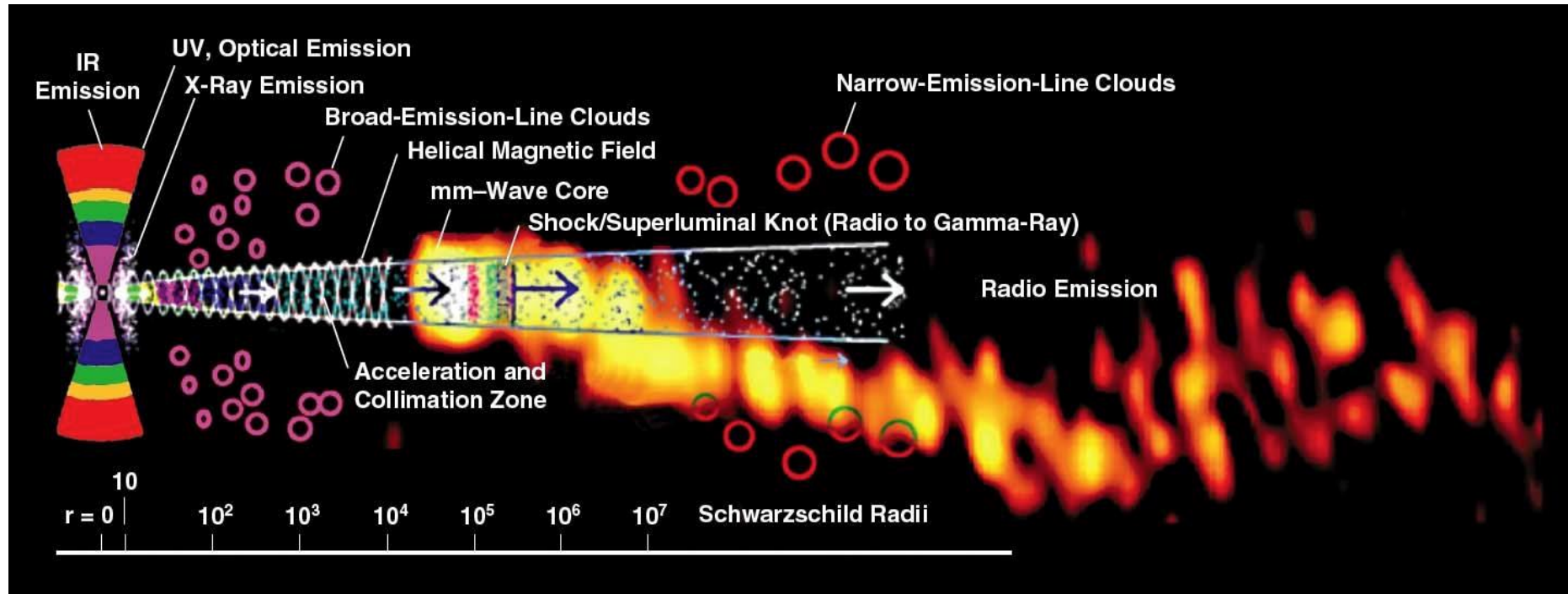
# A last look at Optical vs. Radio Astrometric offsets

# Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),  
Radio continuum image (NRAO/VLA/J. Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

# Active Galactic Nuclei (*Marscher*)



$R \sim 0.1 - 1 \mu\text{as}$

$1 \text{ mas}$

Features of AGN: *Note the Logarithmic length scale.*

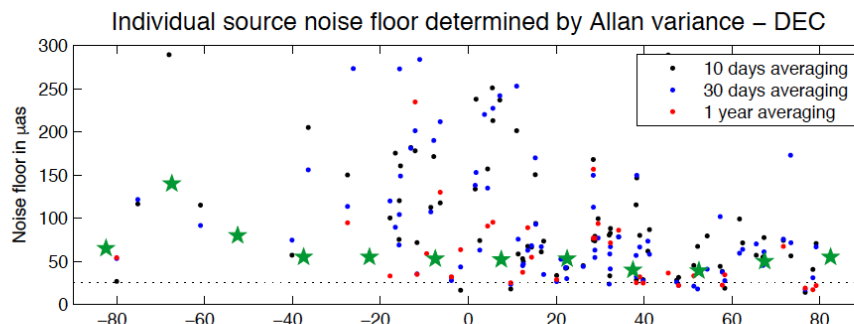
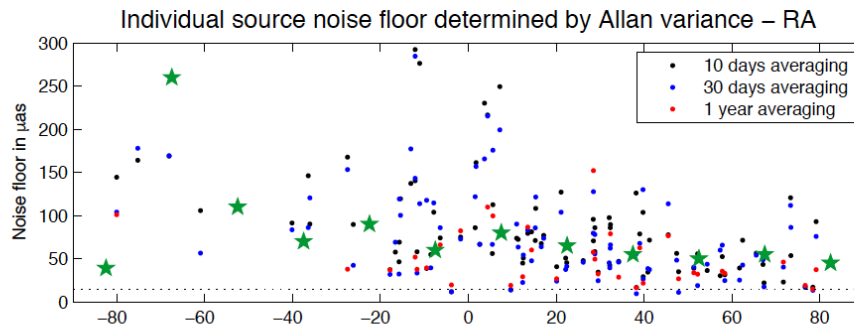
“Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core.”

*Credits: Alan Marscher, 'Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science, VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)*

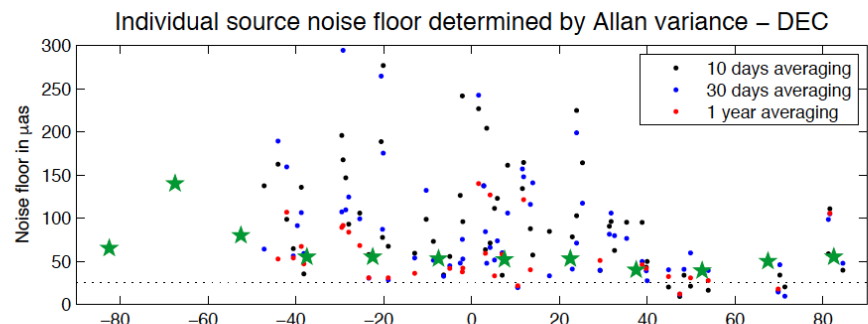
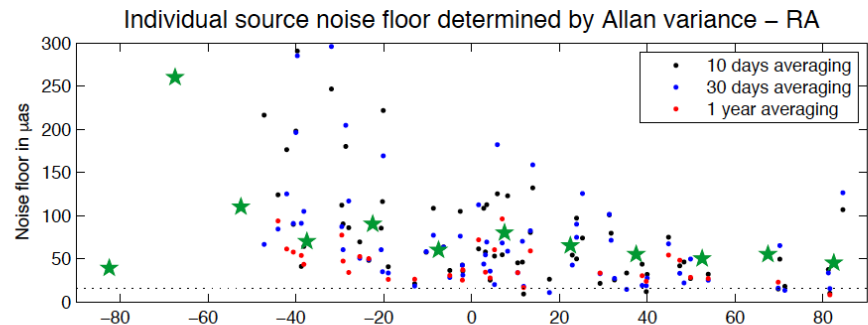
# SX VLBI systematic Floor $\sim 20$ to $30 \mu\text{as}$ ?



## Set of Flicker Noise sources



## Set of White Noise sources



Green ★ : ICRF2 noise floor - average on sources in  $15^\circ$  declination bands.

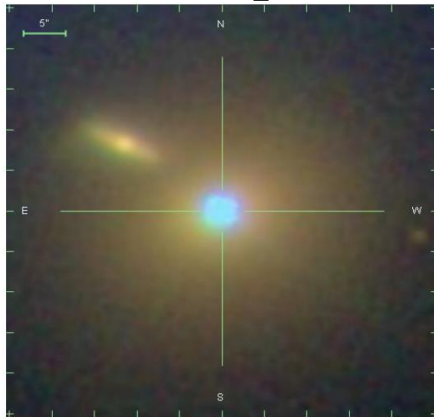
Attention! This method uses ALL “good” sessions, contrary to the decimation test.

Le Bail+ (EVGA, 2017) use Allan variance test on position time histories to determine when **averaging no longer helps—systematic floor is encountered.**

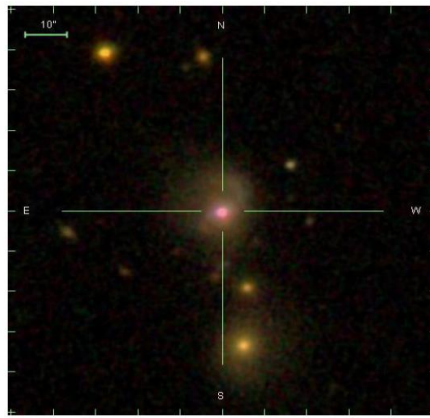
**Structure part of this floor should be several times smaller at K (24 GHz) and Ka (32 GHz)**

# Optical vs. Radio systematics offsets

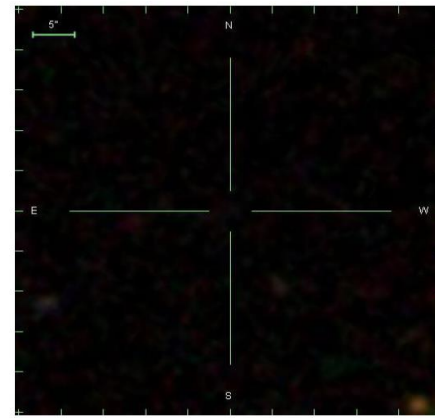
## SDSS Optical images of quasars (scale 5-10 asec)



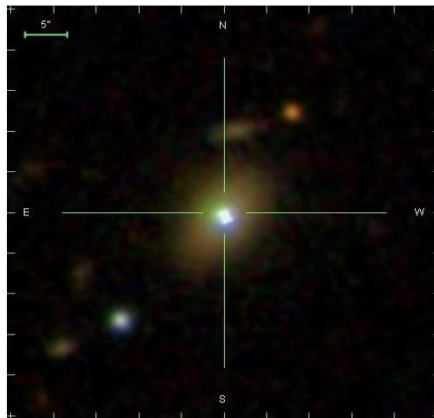
1101+384



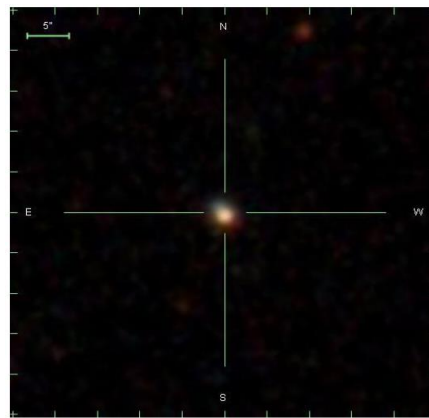
0007+106



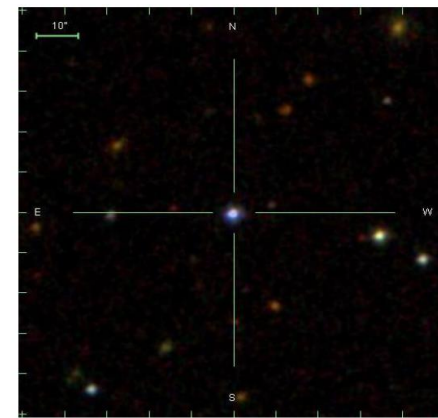
0920+390



1418+546



1514+192

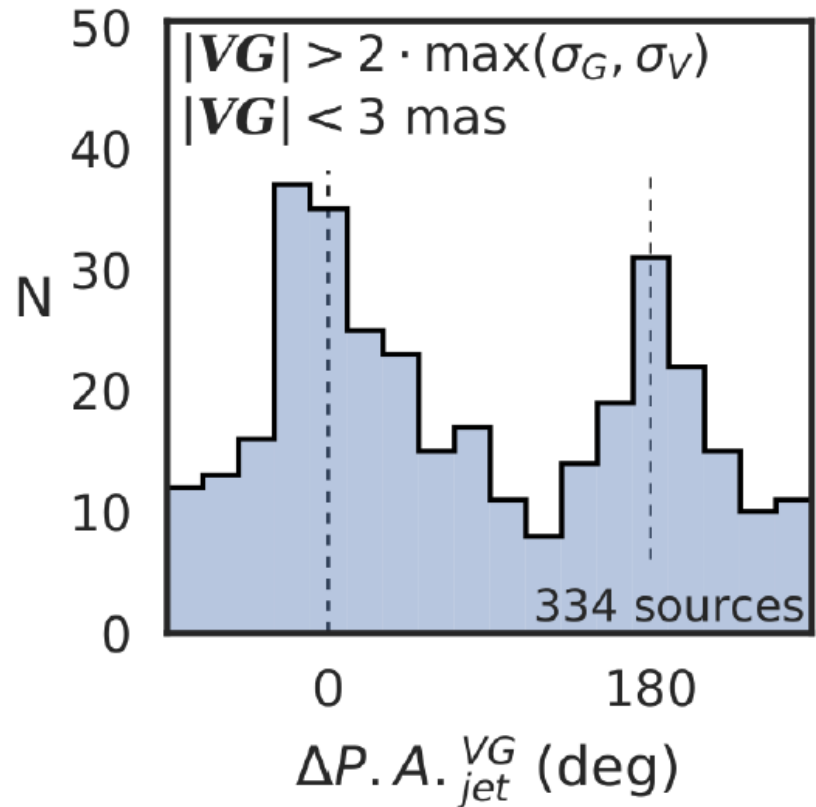
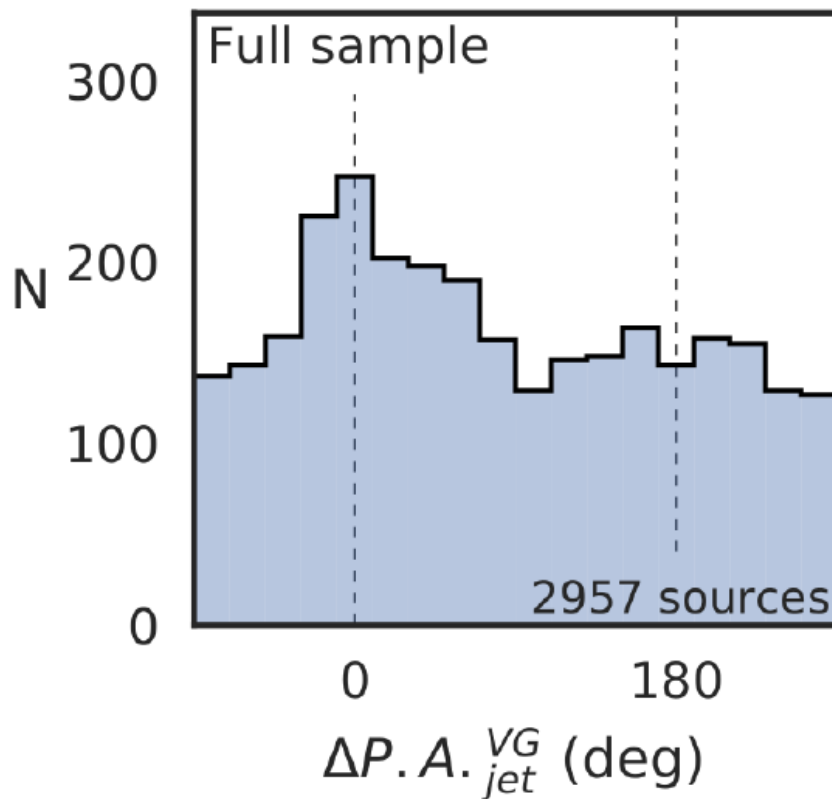


1546+027

Credit: SDSS

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics unknown, fraction of milliarcsecond optical centroid offset?
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

# Optical vs. Radio systematics offsets



Petrov & Kovalev (MNRAS, 2017) show that optical-radio astrometric offsets Correlate with jet direction (or anti-direction).

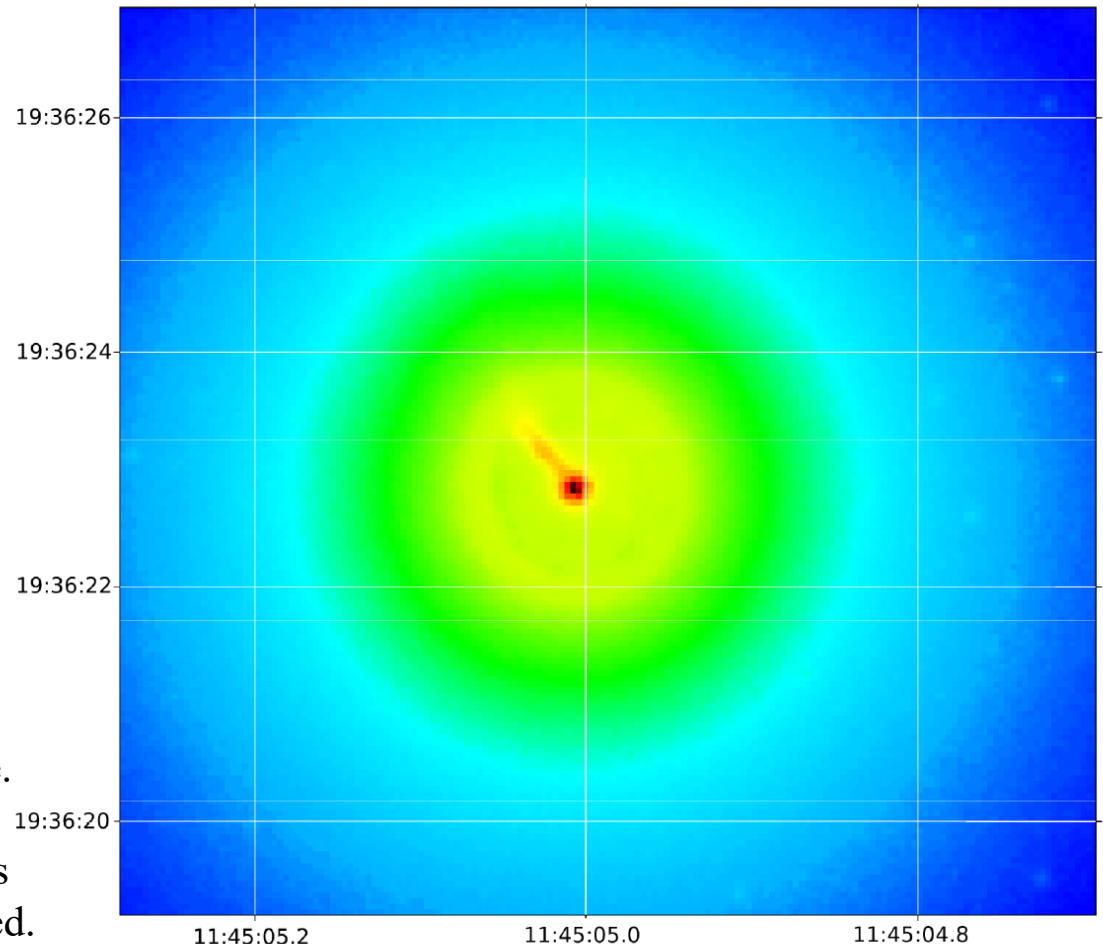
They argue that the offsets are dominated by optical synchrotron jets.

# Optical vs. Radio systematics offsets



Petrov & Kovalev (MNRAS, 2017)

- Example of optical jet in “nearby” 3C 264 would scale to ~milli-arcsecond offsets at typical AGN distances.
- Optical synchrotron jets may be limiting factor in radio-optical astrometric agreement.
- VLBI interferometry “locks” onto the brightest component. Also extremely high resolution resolves out extended structures. So VLBI positions is close of the core.
- Gaia optical image’s centroid averages all of the light distribution, jet included. “Beam” is 60 milliarcseconds.
- Optical may be more easily biased than radio.



**Figure 3.** The archival HST image of 3C264 at 606 nm, HST project ID 13327 (Meyer et al. 2015).



# Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: **synchrotron from jet?**  
non-thermal ionization from corona?  
big blue bump from accretion disk?
- Instrumental errors both radio & optical
- Analysis errors

